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I. INTRODUCTION

In studying the responses of a sense organ it is often useful to compare them with the responses of physical instruments. In this way not only definite and tangible direction is given to the study but the results obtained are related to principles already well worked out. It has been the writer's purpose to approach the present study, so far as possible, from that point of view. The eye, for example, shows a certain similarity in its responses to well known physical recording instruments; one of the points of similarity is a well marked inertia of response. This is exemplified in the lag which is experienced in the rise of sensation when the stimulus is applied and a persistence of sensation after the stimulus is removed. Both of these phenomena are of great importance to laboratory technique and both should be made the subject of more careful investigation if the eye is to be used with satisfactory results in various phases of laboratory work.

When the eye is used as a measuring instrument it becomes especially important to know its characteristics and peculiarities of response. The chief use of the eye as a measuring instrument, so far as the response which we call visual sensation is concerned, is found in photometry. In photometry a balance or equality of two light intensities is established by the eye at a given point or place, namely, the photometric screen.[1] In estab-

[1] This balance, it is scarcely needful to point out, is not in terms of amount of energy of light falling on the screen, but in terms of the power to arouse sensation. This use of the eye in making a balance between two light intensities has often been likened to that of a potentiometer or galvanometer in establishing a balance of potential in an electric circuit by the null method. (See H. E. Ives, Transactions of the Illuminating Engineering Society, 1915, X, p. 103). The analogy, however, is scarcely apt. In establishing a balance of potential in an electric circuit the galvanometer, for example, indicates the balance by giving no response, *i.e.*, it is used in the null method. The adjoining areas of the retina receiving the light from the photometric screen indicate the balance, however, by giving equal responses. That is, the balance obtained could be more accurately compared to the responses obtained in two similar electric circuits by two galvanometers of approximately the same construction, giving equal deflections. A still closer analogy may be found in the case of two similar radiometric instruments which give equal responses.

lishing this balance in photometry (a) the eye is called upon to respond to a wide range of specific stimuli, and (b) its response to these stimuli is selective both in regard to wave-length and to intensity. That is, the amount of response to a given amount of energy is different for the different wave-lengths of light and the amount of difference varies with the intensity as well as with the wave-length of light. Moreover, with regard to both of these points selectiveness is shown not only in the time required to arouse the maximum of response but in the rate of rise to the maximum or in the lag.

This brief introductory statement will probably be sufficient to indicate how important it is in evaluating or choosing methods of establishing the photometric balance or in passing on results in any field in which the response of the eye plays a considerable rôle to know in detail the characteristics of the eye as a recording instrument. It is with the more careful determination of one of these characteristics, namely the rate of rise of the response to the maximum for the different wave-lengths of light that this investigation is concerned. Accurate knowledge of this point has not only a strong claim on scientific interest in its own right but it is of fundamental importance to a decision with regard to the correctness of the balance obtained by a method which is at present much used in the photometry of lights differing in color value, namely a method first described by Ogden Rood, and called by him the method of flicker.[2] Equally important also is its bearing

[2] The method of flicker belongs to the class of indirect methods and at first was little recognized, because the sensation principles upon which it is based were not understood. Of late, however, a growing tendency has been shown to adopt the method both in the field and in the more precise work of the laboratory for the photometering of lights differing in color value. This has not been because of any scientific demonstration of the soundness of the principle on which the method is based, but on account of the higher sensitivity and precision when the lights employed differ widely in color value than is provided by the older and better established method. Space cannot be taken here to show the connection which the difference in the lag of eye's response to different wave-lengths has on the correctness of the balance established by this method. We may quote briefly, however, from a discussion of this point. "Points are enumerated in the paper appended which raise doubt with regard to the correctness of the photometric balance obtained by the method of flicker. Only one of these is discussed, namely, the

on the method of critical frequencies, and on the Talbot-Plateau law, and in fact on all the phenomena arising from giving to the eye in succession light impressions of shorter duration than is required for the sensation to rise to its maximum.[3]

The problem of determining the inertia of response of the eye to different wave-lengths of light presents many points of inter-

influence of the time element in the exposure of the eye to the lights to be compared. With regard to this point, it is shown from experimental data (1) that the sensations aroused by lights differing in color value rise to their maximum brightness at different rates; and (2) that the single exposures used in the method of flicker are much shorter than is required for these sensations to rise to their full value. The eye, therefore, is very much underexposed to its stimulus by the method of flicker. That is, the rate of succession used in the method of flicker is too fast for the single impressions to arouse their maximum effect in sensation and too slow for the successive impressions to add or summate as much as they would need to do to rise to their full value or perhaps even to a higher value than would be given by the individual exposures. Only one other possibility for a correct balance remains,—equality is attained at some value lower than the full value. This can not be assumed, however, without violating well-known laws relating to the factors which influence persistence of vision.

"The principal point of discussion, then, is to what degree it should be held that the difference in lag between the sensations aroused by the single exposures used in the method of flicker is obliterated in a succssion of exposures. Broadly considered, three positions are possible with regard to the point for the rates of succession that are employed in the method of flicker. (1) The difference is not obliterated at all. In this case the photometric balance should deviate from the true balance in direct proportion to the difference in lag for the single exposures. (2) The difference is in part obliterated, but it is still present to a degree which renders the method untenable for precise work. And (3) the difference is entirely obliterated or so nearly so as to be of no practical consequence to the validity of the method. The second is approximately the position taken in this paper. The following evidence is offered in support of this position." (C. E. Ferree and G. Rand: A Preliminary Study of the Deficiencies of the Method of Flicker in the Photometry of Lights Differing in Color. Psychol. Rev., 1915, XXII, pp. 110-163.)

[3] The determination of the time required for sensation to rise to its maximum is also of importance in determining the rate of signalling in case the lights are required to be seen at great distances. An example of this is to be found in the rotating and intermittent lights used in light houses. To have maximum visibility the light should be emitted in any given direction just so long as is required for the sensation aroused by that kind of light to reach its maximum. See "The Perception of Lights of Short Duration at their Range Limits." Blondel and Rey, Transactions of Illuminating Engineering Society, 1912, 7, pp. 625-662.

est. Not all of these can be taken up in the present investigation. It is, in fact, the purpose of the writer to make this investigation only the initial study of a series in which the field will be developed from several points of view. As indicated above, the present study has received its direction largely from current issues in heterochromatic photometry. Because of this the following features will be observed in making the investigation. (a) The determination will be made only in terms of the achromatic or brightness aspect of the sensation. (b) The lights used will be made photometrically equal. This, it is obvious, is essential to the bearing of the investigation on the problem of photometry, for the end point of the photometric observation is equality. The photometric specifications, however, will be supplemented by radiometric specifications. And (c) the determinations will be made for intensities of light selected as far as possible with reference to the photometric problem under consideration.

This being the initial study in a series, the testing and devising of methods will be made an important feature of the work. Up to this time little if any systematic attention has been given by the individual investigators, to a comparative study of methods nor has the control or specification of conditions been such that it is possible to make this comparison from the published work. The following points may be noted with regard to the work that has already been done:

(1) While a number of investigators have made the determinations no two have used methods which are the same in all of the essential details. This has been more nearly done with the direct methods but in these cases no comparison can be made of the results obtained because of the disparity in the experimental technique used, and in the intensity and composition of the lights employed.

(2) No systematic attempt has been made at an equalization of light intensities, either photometric or radiometric and rarely has even an attempt been made at an adequate specification of the light employed.

(3) Some have made the determination in terms of the achro-

matic aspect of the sensation alone, some in terms of the chromatic aspect and some have made both aspects the object of each judgment. Others have made no distinction in the two aspects.

(4) In two cases only have lights of spectrum purity been used; in the remaining cases no attempt has been made to give either a spectro-photometric or a spectro-radiometric specification of the lights employed. Of the two cases in which the stimuli were chosen from the spectrum, a specification in terms of wave-lengths was given in one case; in the other case the part of the spectrum used was roughly indicated in terms of the color of the sensation aroused.

And (5) in most cases no attempt has been made to determine more than the time required for the sensation to reach its maximum, nor were the methods employed devised with any other object in view. Our own investigation, determined partly by the present status of the problem, partly by the special purpose stated above, will comprise the following features: (a) An apparatus will be employed which makes it possible to present the stimuli to the eye in the way that is required by each of the methods that have been used by previous investigators. Thus a comparison of the results obtained by the different methods is not prevented by a disparity of experimental technique. Also by means of this apparatus not only may the lights be taken from a narrow region of the spectrum but the amount used may be specified both photometrically and radiometrically. (b) An attempt will be made to use each of the older methods with the same observer. Also the same amounts and composition of light, will be used, and the general experimental conditions maintained, so that the results obtained by the different methods may be compared. And (c) three new methods will be employed each of which will make it possible directly to compare the different rates of rise of the sensation toward their maximum value, as well as to determine the maximum value itself.

II. HISTORICAL AND CRITICAL

As early as the time of Bacon it was noted that there is an inertia or lag in the response of the eye to light.

"At in visu (cujus actio est pernicissima) liquet etiam requiri ad eum actuandum momenta certa temporis: idque probatur ex iis, quae propter motus velocitatem non cernuntur; ut ex latione pilae ex sclopeto. Velocior enim est praetervolatio pilae, quam impressio speciei ejus quae deferri poterat ad visum."[4]

Beudant[5] states that an object which moves with extreme rapidity before the eye is not perceived because sensory impressions are not made on the eye instantly. Plateau[6] made the observation that when a square of white paper is passed rapidly before the eye it appears not white but gray. He was also the first to express the belief that color sensation does not come at once to its maximum. Swan[7] noticed "that the light of the sky seen immediately over a ball in its descent through the air, seemed less bright than at those parts of the retina where the action of light had not been interrupted by the passage of the dark body." He conducted some experiments also to determine the intensity of light sensation with short exposures. Subjecting the eye to the action of lights of different intensities for intervals ranging from 1/100 to 1/16 of a second, he found that "colorless lights of different intensities produce like proportions of their total effect on the eye in equal times." He did not directly determine the interval required for the light sensation to come to its maximum, but he estimated it from the results of his experiments with short exposures to be about 1/10 of a second. The task of experimentally determining the interval required for the sensation to come to its maximum was not begun, in fact, until 1868

[4] Novum Organum, 1711 lib. ii. Aph. xlvi.

[5] Essai d'un Cours Elementaire et Général des Sciences Physiques; Partie Physique, 1815, p. 480 de la 3 me edition.

[6] Nouveaux Memories de l'Academie Royale des Sciences et Belles Lettres de Bruxelles, 1834, viii, p. 53.

[7] Trans. Roy. Soc. Edinb., 1849, XVI, pp. 581-603.

when Exner, working in the laboratory of Helmholtz, definitely formulated the problem and proposed a method for its solution. In the work thus inaugurated two classes of methods have been employed, the direct and the indirect. Although simpler in form the direct methods have been the later to be used in making the determination. The principles on which these methods are based, were first employed in a crude form by Swan in 1849 in his experiments on the effect on the eye of short exposures of light. They were not developed and applied to the more specific problem, however, until a half century later, by which time most of the work with the indirect methods had been completed. In the order of development, then, the indirect methods came first. In the presentation here, however, this order will be reversed and the direct methods will be considered first. This will be done for two reasons, (a) because the direct methods logically precede the indirect, and (b) because it will be easier to understand why the indirect methods have been resorted to when the difficulties attending the application of the direct methods are made clear.

A. The Direct Methods. A direct method was first applied to the determination of the time required for a sensation to come to its maximum by Charpentier in 1887. Direct methods were later used by Broca and Sulzer in 1903, by Buchner in 1906, and by Berliner in 1907. In the presentation of the work of these men, the chronological order will again be deviated from and the work of Broca and Sulzer will be considered first. This is done because the fundamental principles upon which the direct methods are based, can be presented and discussed more conveniently and comprehensively from their work as a basis than from the work of their predecessors. The reasons which may be offered for this are: (a) although these methods all sustain a close logical relation to the standard method of photometry, namely, the equality of brightness method, Broca and Sulzer have deviated the least from the type in the development of the method and in its application to the detection of lag; and, (b) not only have they used the equality of brightness method more correctly than their predecessors, but they have attacked their problem much more systematically and have used better methods of physical control.

(1) *Broca and Sulzer.* As used by Broca and Sulzer in 1903 the method is as follows. Two surfaces were illuminated by the light, the effect of which on sensation for different lengths of exposure time was to be determined. One of these surfaces was chosen as the standard and the other was compared with it, in a series of judgments of equality. Before beginning each experimental series the two surfaces were made of equal brightness and the photometric value of the equal illumination was determined. During the series of judgments the standard surface was illuminated continuously and the comparison surface for .01, .02, .03, etc. seconds, according to the needs of the problem. With each change in the time of illumination of the comparison surface the intensity of light on the standard surface was altered until the two were judged of equal brightness. The photometric value of the light falling on the standard surface was determined in each case and this was taken as the sensation value of the comparison light for the length of exposure used. From the experiments thus conducted a series of photometric values was obtained, for different intervals of exposure to the comparison light. These values were plotted in the form of a curve which was believed by Broca and Sulzer to show the rate of rise of the sensation to the maximum as well as the maximum itself.

While the method is commendable in its simplicity and is of a type that would naturally appeal to the photometrist it is open to two serious criticisms. (1) The attempt to rate sensation for comparative purposes in terms of photometric units is, it is obvious, fundamentally wrong. For example, a foot-candle may be defined as the amount of light falling on a unit surface at a distance of one foot from a standard candle or a lumen on a square foot; the amount falling on a similar unit of surface at a distance of one-half foot from the standard candle would then be four foot candles. Rated in photometric units the illuminations of the two surfaces would sustain to each other the ratio of 4:1. The sensations aroused by the two surfaces cannot, however, be said to sustain the ratio of 4:1. When inspecting the curves of Broca and Sulzer, therefore, it must be borne in mind that the plotting is done in terms of photometric units and

not in terms of sensation[8] nor even in just noticeable changes from the zero of sensation. (2) The attempt to employ unmodified the photometric method to determine the effect on the eye of short exposures to the comparison light—all differing in value from each other and from the exposures to the standard light—is, in reality, based upon a grave misconception of the use of the eye as a measuring instrument. In photometry neighboring surfaces of the retina are exposed to the standard and comparison lights. These two surfaces, as already stated, may be likened roughly, to two recording instruments, approximately identical in kind and capable of independent response. If these two lights are of the same intensity and composition and are exposed the same length of time, the same responses will be recorded. If, however, the exposure be for different lengths of time, different responses will be given. Since in the usual practice of photometry the intervals of exposure are of the same length, the time element, so far as the essential correctness of the balance is concerned, may be ruled out of consideration and the two receiving surfaces may be used to equate light intensities at the photometric screen in terms of their power to arouse sensation.[9] If, however, one surface were exposed longer than the other as is the case, for example, in the determination of the rise of sensation, the two surfaces could no longer be used for this purpose, unless indeed the eye were calibrated for the one and the response to the other were rated in terms of the calibrated values.

[8] It is not our purpose to raise here the mooted question whether or not it is possible to establish a unit of sensation. We would prefer rather to leave that question in abeyance and to make our expression of the rise of sensation in terms of just noticeable changes from the zero value. We believe nothing more can be done at this time with safety. In doing this, moreover, it is not to be understood that we are subscribing to Fechner's belief that these just noticeable changes, as sensation quantities, are equal in value. That question, also, is left entirely open.

[9] This, of course, is strictly true only when the lights compared are of the same composition. It cannot be said, for example, that a balance made for lights differing in composition would hold for any other intervals of exposures than the ones used, even though the intervals are equal. That is, sensations aroused by lights of different composition neither rise nor decay at the same rate, hence an equality value between such lights is valid only for the interval of time used.

But, it may be said that in the determination of lag, the problem is not the equalization of light intensities, which demands that the lights compared act on the eye for equal lengths of time or that a calibration or correction factor be applied. There is no attempt in this determination at an evaluation of a stimulus by means of the eye. The problem ends with the matching of the standard and comparison sensations. These considerations render it none the less necessary, however, that if the comparison sensations are to be rated from minimum to maximum value the variable influence of the time element on the standard sensations must be eliminated from the experiment. The method must provide a series of representative -standard sensations graded in brightness to which to match the comparison sensations for the different intervals of time. In the failure to provide such a series as a standard, lies the weakness of the method so far as it has been developed up to the present time. The failure of Broca and Sulzer to establish this standard depends in part at least upon their misconception of the temporal course of sensation after it has reached the maximum. In preliminary observations they had found that sensation rises to a maximum, then for a very brief space of time decreases in value. They did not, however, carry the observation far enough to learn that this decay continues and although it takes place more slowly is just as characteristic of the temporal course of sensation as is lag. They assumed that there is a permanent level of sensation, and that the maximum is in reality an over-shooting of this level. The permanent level, they believe, is attained in about two seconds, hence any exposure of the eye to the stimulus for two seconds or longer guarantees a constant response in sensation. The sensation from the standard light could then, they believed, be graded in terms of the stimulus and all that was required in the problem of determination of lag was to expose the comparison light for the required interval and find that intensity of standard light which, when exposed two seconds or more, would give a sensation matching in brightness the sensation given by the comparison light. Indeed, so sure were they of the permanency of the sensation after two seconds of exposure to the

stimulus that they made no attempt to have the intervals of exposure equal in the several cases. The only requirement was that these intervals be equal to or longer than two seconds.

In detail the application of the methods was as follows. Determinations were made for white light and for the colors red, green, and blue. In the work with white light the following apparatus and method for making the exposure was used.[10] A

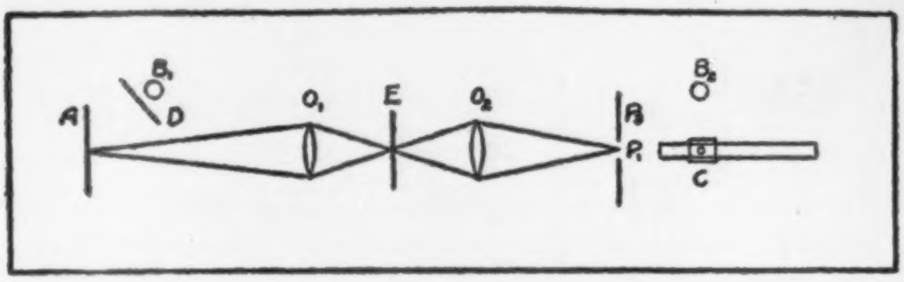

FIGURE 1

white card A was illuminated by a lamp B, enclosed in a lamp-house. This lamp-house was provided in front with a "Blondel" diaphragm D to regulate the amount of light emitted. The light reflected from A is focused by means of a lens O_1, on an episkotister E. Spreading from this image the light is again focused on an opening P_1, in a screen. On this screen adjacent to P_1, is fastened a cardboard P_2, having the same coefficient of reflection as A and of the same size as P_1. This is illuminated by a second lamp B_2 provided with a housing and a Blondel diaphragm similar to B_1. P_2 is made the standard surface and P_1 the comparison surface. The length of time P_1 is illuminated is controlled by the size of the open sector in E. This open sector was rotated at a rate which allowed an interval of one second[11]

[10] See "Les fonctions retiniennes en fonction du temps," Annales d'Oculistique, 1904, 131, p. 107.

[11] It is questionable, of course, whether the same value per exposure is given to sensation by a succession of exposures separated by an interval of one second as is given by a single exposure. Broca and Sulzer's own results seem to indicate that there is not the same effect. For example, they say that when the exposures are one second apart the sensation aroused by the first is not so bright as for the succeeding exposures; also that when a longer interval is used between exposures, the sensations aroused are not so bright, until quite a number of impressions have been made, as they are when the interval, one second, is used. Both of these statements seem to indicate that a summation effect of one impression upon the other was present.

to elapse between the successive exposures. P_1 and P_2 were viewed through a tube C.

In the work with colored light a different apparatus was used, although the principle of experimentation was the same.[12] In

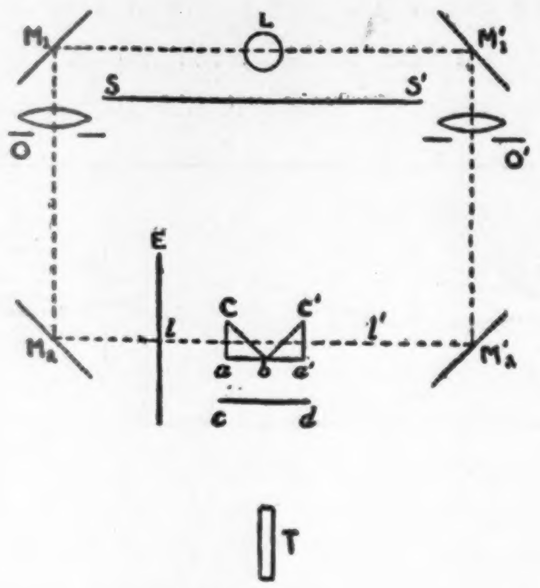

FIGURE II

general this consists of a source of Light L (acetylene) and two identical optical systems, one of which is made up of mirrors M_1 and M_2, a lens, and the total reflecting prism abc; the other, of the mirrors M_1^1 and M_2^1, a lens and the total reflecting prism a′ b c′. The first of these gives the comparison light to the eye; the second the standard light. At E is an episkotister on which the light reflected from the mirror M_2 is focused. By means of this episkotister the time of exposure of the comparison light is regulated. At c—d is placed the filter by means of which the colored light is separated out from the white light. S—S′ is a screen which protects the eyes from direct light from L, and T is a tube through which the standard and comparison surfaces are viewed.

The results obtained in this work were expressed in the form of curves in which the photometric value of the standard light, given in lux, was plotted against that interval of exposure of the

12 "La sensation lumineuse en fonction du temps, pour les lumières colorees." "Journal d'Physiol,' 1904, vi, pp. 55-68. Also "Comptes Rendus des seances de l'Academie des Sciences," 1903, CXXXVII, pp. 944-979.

comparison light for which the judgment of brightness equality was made at the photometric screen. This gave, by the terms of the method, the photometric rating of the comparison light for different intervals of action on the eye. Figure III is a reproduction of their curves. An inspection of these curves will show among other things that although, as stated earlier in the paper, Broca and Sulzer have made no systematic attempt to equate their stimuli in brightness, they have in all cases given a photometric specification of the lights used. In some cases, moreover, the colors have had equal photometric values. By the phrase "permanent sensation line," they have designated the sensation value for a given light at any time after it has been exposed to the eye for two or more seconds. That this designation is based on a false conception of the temporal course of sensation, scarcely needs again to be pointed out. Sensation does not attain to a constant level at the end of two seconds. It must be remembered, therefore, that the shape of the curves given by Broca and Sulzer depends both upon the rate of exhaustion of the eye by the standard light and the actual rate of rise of sen-

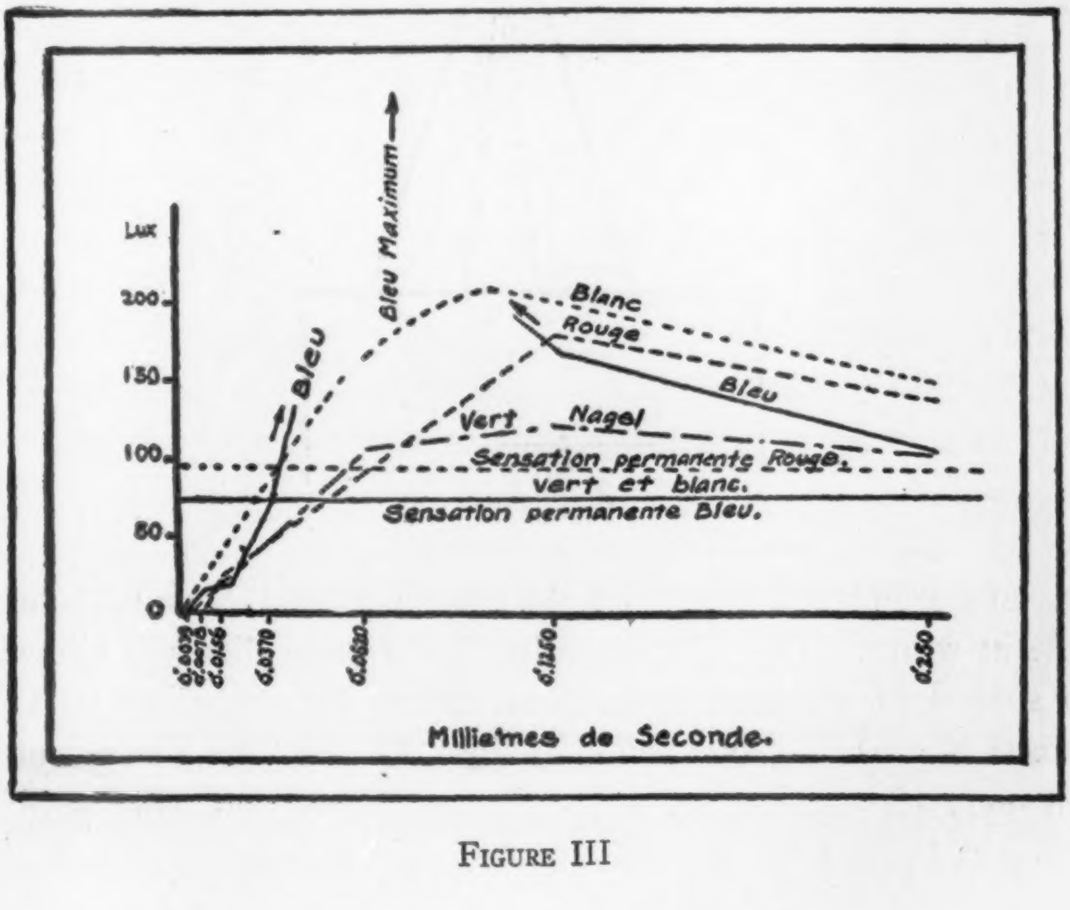

FIGURE III

sation to its maximum. The effect of differences both of wave-length and intensity of light upon the rate of exhaustion of the eye, and of rate of exhaustion upon the results obtained by the method will be taken up later in the discussion of the method.

As used by Büchner and Berliner the direct method was improved in general principle by giving to the standard light a constant interval of exposure.

(2) *Büchner*. The object of Büchner's work[13] was to determine the effect of difference of intensity on the time required for the sensation aroused by white light to come to its maximum, and to plot the rise of sensation to its maximum, under conditions of both light and dark adaptation. The method by means of which his stimuli were presented to the eye was similar to that previously employed by Lough (see this paper p. 19). For work with dark adaptation the arrangement of apparatus was as follows. (See Figure IV.) A milk glass screen M was illuminated from behind by an arc lamp B. In front of this

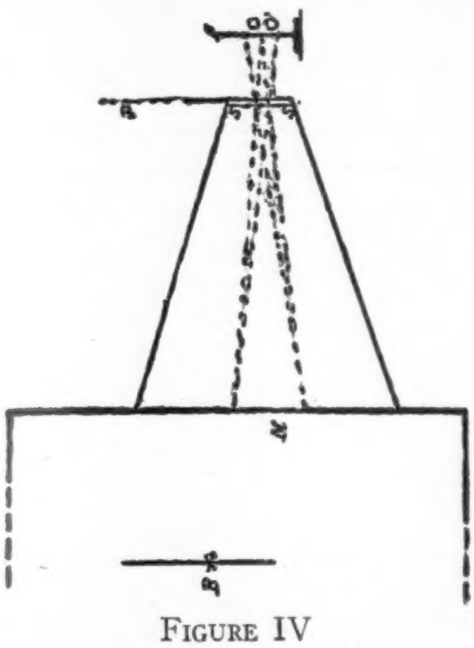

FIGURE IV

screen were placed, one above the other two slits, S and S′, variable in width. The light emerging from these slits was allowed to spread to a second milk glass screen, F, producing on this screen two continguous bands of light, O and O′. These bands

[13] "Über das Ansteigen der Helligkeitserregung." Psychologische Studien, 1906-1907, II, pp. 1-29.

were viewed directly by the observer. The regulation of the time of exposure of these luminous areas to the eye was accomplished by means of a pendulum provided with two openings, one in front of S and the other in front of S′. The opening in the one which exposed the standard light was kept constant, and the opening in the one which exposed the comparison light was varied. With a given time of exposure of the comparison light, the intensity of the standard light was varied by changing the width of slit S until the two lights appeared equal at the moment of their disappearance. The time of exposure of the comparison light for which the widest value of slit S had to be used was taken as the time required for the comparison light of a given intensity to reach its maximum value. The method was thus similar to that employed by Broca and Sulzer with the exception a) Broca and Sulzer plotted the increase of the standard light required to match the sensation aroused by the comparison light for the different lengths of exposures in terms of photometric units while Büchner plotted these values in terms of slit widths and b) Büchner used a constant interval of exposure of the standard light.

The following values were obtained for the development time. These values, it is stated, are only approximate.[14]

TABLE I

Intensity	*Development-Time*
0.072 M.C.	0.230 Sec.
0.145 M.C.	0.200 Sec.
0.260 M.C.	0.120 Sec.

For the work with light adaptation, a different arrangement of apparatus was used in order that a higher intensity of light

[14] So far as we can tell from Büchner's report of his work, there was no means of keeping the spots of light, which served as his standard and comparison, of constant area. The vertical dimension was constant, determined by the constant vertical dimension of the opening in the pendulum used to make the exposures, but there was no provision to keep the horizontal dimension from varying with the distance of the screen from the mirrors. In all probability the area of the surface exposed has also an effect on the development-time since, within limits, increase of area stimulated increases the intensity of the sensation aroused. At least, it cannot be assumed, prior to experimentation, that this was a negligible factor.

might be gotten. Light from the lamp B (Fig. V) was thrown on a translucent screen F′ by two mirrors Sn and Sv. Sn re-

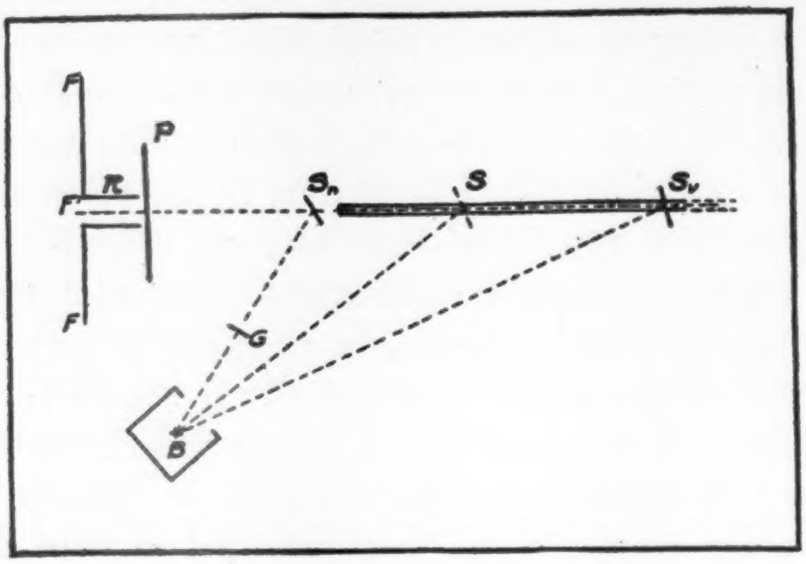

FIGURE V

flected light to the upper half of the screen, Sv to the lower half. The intensity of these images was varied as needed by changing the distance of the mirror Sv from the screen, and by interposing a dark glass (g) between the source and the mirror Sn. The method of regulating the time of exposure and the general principle of working were the same as for the work with dark adaptation. The results obtained are as follows:

TABLE II

Intensity	*Development-Time*
9 M.C.	.060 Sec.
15.5 M.C.	.070 Sec.
57 M.C.	.033 Sec.

No comparison is made of the time required to arouse the maximum of sensation under conditions of light and dark adaptation with lights of the same intensity. Besides stating that a difference in the intensity of the light used affects the development time, Büchner reports also two other points. (1) The sensation does not rise regularly to its maximum value, (see curves op. cit., pp. 14-24), and (2) the rate of rise is different for different parts of the retina. Only rough experiments were conducted, however, to show the latter point.

(3) *Berliner's*[15] investigation had a two-fold object: (a) a determination of the time required for color sensations to reach their maximum saturation and (b) the time required for them to reach their maximum brightness. The general principle of experimentation was the same as was used by Büchner. The work on the rise of the sensation to its maximum saturation will be described first. Colored lights were obtained by means of pigment papers and gelatine filters. For the work with pigment papers a rotating disc was used made up of sets of variable sectors of colored and gray paper, outer and inner. One of these was made the standard and the other the comparison stimulus. For the comparison stimulus the colored and gray sectors were given a value which would produce, when the disc was rotated, a color of the desired degree of saturation. The proportion of colored and gray sectors in the standard disc was altered until the two were of equal saturation, at the moment of disappearance of both stimuli. The time of exposure to each stimulus was regulated by means of the same kind of pendulum as was used by Büchner. One of the openings in the exposure device carried by the pendulum passed in front of the standard stimulus; the other, in front of the comparison. The eye of the observer was screened from all of the disc but the part in front of which the exposure apparatus passed. From these experiments with pigment papers, green, red, blue, and yellow, Berliner concluded that color sensations all reach their maximum saturation in approximately the same length of time. This time he found to be about 0.300 seconds. In his experiments with the colored gelatine filters the saturation of the standard stimulus was varied to suit the needs of the experiment by rotating in front of one half of the gelatine plate an episkotister, the closed sectors of which were covered with a gray of the brightness of the color. The method of exposing the stimuli and of detecting the development-time was the same as for the pigment papers. Again each of the four colors reached its maximum saturation in approximately 0.300 seconds.

In his determination of the time required for the colors to

15 "Der Anstieg der reinen Farbenerregung im Sehorgan" Psychologische Studien, 1907, III, pp. 91-155.

reach their maximum brightness only two colors were used. These colors were obtained by means of gelatine filters. The experimental procedure was the same as was employed for the determination of the time required for the colors to reach their maximum saturation, with the exception that the closed sectors of the episkotister used to vary the brightness of the standard stimulus were made black instead of the gray of the brightness of the color. The maximum brightness of each of these two colors was attained in approximately 0.130 seconds. Berliner also mentions the irregularities in the rates of development of the color sensations. This was especially true of their rise in saturation.

(4) *Charpentier.* Charpentier[16] determined the effect of difference of intensity on the time required for white light to produce its maximum effect in sensation. Working with four intensities of light, he derived the law that the time required for the sensation to reach its maximum value varies inversely as the fourth root of the intensity of the light. He does not fully describe his method of working; but, so far as can be determined from the description given, it is considerably cruder than that employed by Broca and Sulzer, Büchner, or Berliner.

(5) *Lough.*[17] Lough, 1896, worked also with white lights of different intensities. With regard to the effect of intensity on the rate of rise of sensation he came to the following conclusions. (1) The time required for the sensation to reach its maximum varies with the intensity of light. An increase in the intensity of light decreases the time required for the sensation to come to its full value. (2) For intervals of exposure less than is needed to bring the sensation to its maximum value, the intensity of sensation varies directly as the time of exposure. The effect of intensity on the time required for the sensation to come to its maximum is shown in the following table. The in-

[16] Recherches sur la persistance des impressions rétiniennes et sur les excitations lumineuses de courte durée. Archives d'Ophtalmologie, 1890, X, pp. 107-135.

[17] "The Relations of Intensity to Duration of Stimulation in our Sensation of Light," Psychological Review, III, 1896, pp. 489-492.

tensities of the lights used are not specified in standard units. Only ratios are given in an arbitrary scale.[18]

TABLE III

Intensity of Light	*Time of maximum effect*
1	0.148 Sec.
4	0.110 Sec.
16	0.100 Sec.
64	0.085 Sec.
256	0.090 Sec.

In making these experiments Lough used the following apparatus. The light employed in making the determinations came from two standard candles, a and b, (See Fig. VI) which could

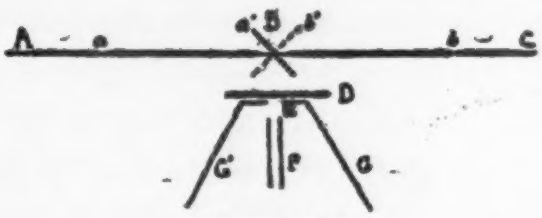

FIGURE VI

be slid back and forth on two wooden arms, AB and BC, one slightly above the other. The light was reflected through a slit E into the observation tube F by means of a mat white reflector a′ (coefficient of reflection not given) and the light from b by means of a similar reflector b′, which is slightly above or below a′. Slit E is one centimeter wide and four centimeters high. The upper half of this slit is illuminated by the light from a′, and the lower half, from b′. The eye is protected from the direct light from a and b by means of the tube F and the screens, G and G′. Between a′ and b′ and the slit E swings the exposure apparatus D, which is a pendulum carrying a mat black screen. This screen contains two open sectors, S and S′, not shown in the figure, one twice as broad as the other. Lough describes the method of detecting the maximum as follows:

"In order to obtain the time for the maximum effect, the lamps were placed so that a′ and b′ gave sensations of equal intensity and S and S′ were then adjusted to the relation of 1 : 2. When now the pendulum was allowed to swing through a small

[18] The unit of intensity used by Lough, worked out roughly from the data given by himself, is 0.097 meter candle.

arc the two reflectors seemed equal, but as the amplitude of the swing increased, a point was soon reached where a′ appeared just preceptibly darker than b′. This marks the point where a′ fails to produce its maximum effect. With openings and lamps adjusted as before, the pendulum was now given a much larger swing. This caused a′ to appear much less intense, while b′ retained its former intensity. The amplitude of swing was gradually decreased; with this a′ becomes gradually more intense until it finally becomes equal to b′; after this no further change will take place. This also marks the point of maximum effect for a′."

(6) *Martius.* The form in which Martius[19] employed the direct method of making the determination seems also to be open to question. The surfaces to be compared filled the visual fields of two telescopes. The standard light illuminated the field continuously, while the time of exposure of the comparison field could be varied. The observer looked first at the standard light, then quickly moved his eye to the other telescope and viewed the comparison light. The maximum was determined by a series of observations similar in principle apparently to those made by Broca and Sulzer. Two conspicuous errors were involved in Martius' method of making the determinations. (1) Even less adequate provision was made for standardizing the sensation which served as standard than was made, for example, by Büchner and Berliner. And, (2) a serious time-error was involved in making the comparison of the two fields. That is the two sensations were not compared directly. One was compared with the variable or changing memory of the other. The seriousness of this error will be obvious to any one who is familiar with the difficulty of making accurate and reproducible judgments for such short intervals of exposures, even when they are made under the most favorable conditions. The exposure apparatus employed by Martius is somewhat elaborate. A schematic representation of this apparatus, drawn by the author, from his description is shown in Figure VII.

The discs D and M, are connected by a transmission gear in

[19] "Über die Dauer der Lichtempfindungen" Beitrage zur Psychologie und Philosophie, 1905, I, pp. 275-366.

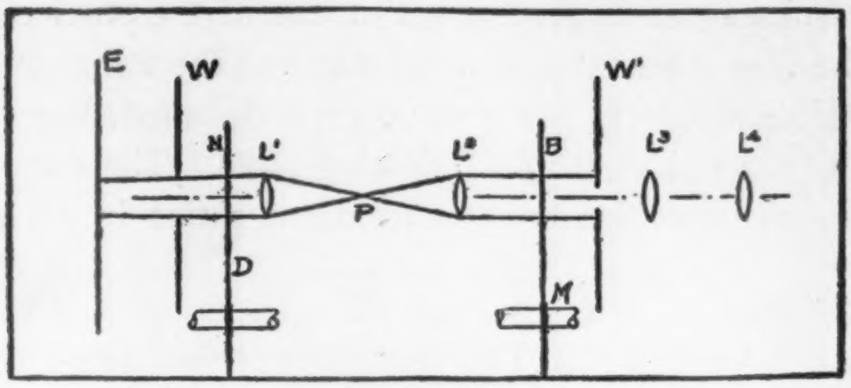

FIGURE VII

such a manner that they may be rotated at different rates. These discs allow the light to pass from the source to the eye, only when the openings, N. and B, come at the same time into the line of sight. The times of exposures and the time between exposures can be reckoned from the relative positions of the openings, N and B, and the speed of rotation of the two discs. The light is presented to the eye in the following manner. An illuminated mat surface, E, serves as the source of light. The light from this passes through an opening in a screen W, and from there through the lens L′ and focuses at P. From P it spreads to the lens, L^2, and is rendered parallel, passing just through a slit in screen W′ and then through the telescope lenses, L^3 and L^4, to the eye. At each exposure the eye viewed the field of the telescope uniformly filled with light. Two of these apparatus were provided, side by side, one to give the standard stimulus and one the comparison. In either, the exposure discs could be rotated if desired. They were rotated, however, only in giving the comparison stimulus. In giving the standard stimulus the light was allowed to come through to the eye continuously. The apparatus used by Martius may be criticised in two regards. (1) The arrangement was such that the standard and comparison lights were presented to the eye successively rather than simultaneously which, as has already been noted, introduced a serious time-error, and (2) the position of the exposure discs in the path of light were not such as to expose or to cut off the light sharply. To accomplish this the light should have been focused in the plane of the discs.

His results agree in general with those of the other observers, in that he found that the more intense was the light, the shorter was the time necessary for it to produce the maximum response. The results are given in the following table. The intensities of light used are specified only in terms of ratios in an arbitrary scale.

TABLE IV

Intensity	*Time required to produce maximum response*
1	0.013 Sec.
1/2	0.039 Sec.
1/4	0.053 Sec.
1/8	0.066 Sec.
1/16	0.078 Sec.
1/32	0.093 Sec.

Martius also carried out a few rough experiments with colored lights, coming to the following conclusion. "If the colors rank from bright to dark in the following order, yellow, green, blue, red, they rise to their maximum in the order yellow, blue, green, red." He gives the appended table.

TABLE V

Color	*Time required to produce maximum response*
Yellow	0.020 Sec.
Blue	0.036 Sec.
Green	0.048 Sec.
Red	0.090 Sec.

B. The Indirect Methods. (1) *Exner*[20] working in the laboratory of Helmholtz, was the first to take up the investigation of the response of the retina to lights of short duration by an indirect method of determination. His method was based on the following principle.[21] If the stimulus for a light sensation is cut off before it has aroused its maximum response in sensation, the sensation will continue in its original brightness, *i.e.* there will be a positive after image. When, however, the stimulus is cut off after it has produced its maximum effect, the sensation will tend to continue in the reversed brightness, *i.e.,* there will

[20] Über die zu einer Gesichtswahrnehmung Nohtige Zeit." Sitzungsberichte der Kaiserlichen Academie der Wissenschaften, 1868, LVIII, pp. 601-631.

[21] Helmholtz apparently saw the possibility of a defect in this principle. Handbuch der Physiologischen Optik, 1896, pp. 513-514.

be a negative after image. Now, if two adjacent parts of the retina are stimulated by lights of the same intensity, but one excitation is begun slightly before the other, two sensations will result, the course of which may be represented by the curves in Figure VIII. From these curves, granting the principle pre-

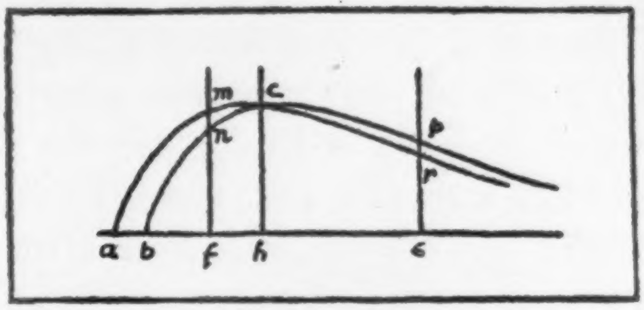

FIGURE VIII

viously stated, it will be seen that if the two stimuli are interrupted simultaneously before either has reached its maximum (represented in Fig. VIII by m, n, f) both should give positive after images but these after images should be of different brightnesses. That is, the after image of the stimulus, the exposure of which was begun first, will be the brighter. If they are interrupted after both have passed their maximum (represented in Fig. VIII by p, r, e) both should give negative after images, which should also differ in brightness. There is a time, however, at which they may be interrupted (represented in Fig. VIII by c, h) when the result should be two positive after images of equal brightness. The sensation aroused by this length of exposure is, Exner believes, the maximum for the light first exposed. The following comments may be made both on the principle on which the method is based and on the limits of application of the method to the problem in question. (1) It can scarcely be demonstrated within the limits of accuracy required for the method that an under-exposed and a fully exposed eye give positive after responses and an eye barely over-exposed gives only a negative response. The assumption is based on a very general consideration of the shape of the intensity curve for sensation—that is, the sensation rises to its maximum then begins to decay if the stimulus is prolonged—and on Helmholtz's theory of the correlation of the negative after image with the

loss of sensitivity and the decay of sensation. (2) The general principle of detecting the maximum by two exposures, one beginning slightly after the other could be used quite as readily, were the judgments made of the sensations aroused during the exposures instead of the after-responses. There seems in fact even no theoretical justification for making the judgment of the after-images unless it is believed that the brightness reversal which according to the assumption should occur as soon as the point of maximum intensity is passed for the sensation first aroused, would make a greater and, therefore, a more readily detectable difference between the after-images of the two sensations than would be obtained between the two sensations themselves. In contradiction to this, however, Kunkel, the next to take up the work of detecting the time of maximum response, declared the judgment of the after-images to be impossible and used the method with three revisions, one of which was that all judgments were made of the sensations directly aroused by the two exposures. (3) The sensation aroused by the light first exposed is the sensation whose maximum intensity is being determined. Now, if the second exposure is begun too long after the first, the judgment of equality will be made after the sensation aroused by the first exposed light has reached its maximum. If, on the other hand, it is begun too soon after the first, the two sensation curves will too nearly coincide and the judgment of equality will be made for too great a part of the two curves, when theoretically it should be made at a given point in the curve or, at least, for a very small segment of the curve. That is, by the first procedure, greater sensitivity is obtained in detecting the equality point, but the equality point does not coincide with the point of maximum intensity; while, by the second procedure, a lesser sensitivity is attained in detecting the equality point, but the point of maximum intensity lies within the segment judged equal. Obviously a successful application of the method should come from a proper compromise between the two procedures, or the choice of the proper interval of time between the beginning of the exposure of the eye to the first and second stimulus. Both exposures end at the same time, hence,

once this interval between the two exposures is chosen, the two are varied by equal amounts until the judgment of equality is made.[22] (4) At best the method can be used only for obtaining the exposure time required to give the maximum intensity of sensation. The relative sensation values of exposure-times less than this can not be determined directly. But once having obtained by Exner's method, the maxima for a series of sensations graded in intensity, the curve for a third sensation, the maximum intensity and the time of development of which is equal to or less than the last one of the graded series, might be determined by the method of direct comparison or equality of brightness. This combination of the two methods, however, has not yet been made.

Exner used only white light in making his determinations. Four intensities which bore the ratio to each other of 1, 2, 4, and 8 were used. The intervals necessary for these different intensities to have maxmium effect in sensation ranged from 0.287 to 0.118 seconds. With reference to the effect of intensity of stimulation on the time required for sensation to reach its maximum he draws the following general conclusion:

"Wenn die Reizungs-Intensitäten in geometrischer Progression wachsen, so nehmen die Zeiten, die zwischen Beginn der Reizung und ihrer höchsten Intensität verlaufen, in arithmetischer Progression ab."

(2) *Lamansky.* · Lamansky[23] was the next to take up the work of determining by an indirect method the time required for the visual sensation to rise to its maximum. He gives in the article cited an extremely brief description of his work. No account of the method used is given further than the statement that it was the same as used by Exner. Pigment papers, white and colored, were used as stimuli. A detailed statement of results is not given. The general conclusion is drawn that the

[22] The above comment is perhaps more strictly applicable to the judgment of the sensations than to the judgment of the after-images. It is somewhat difficult to say *a priori* just what the situation would be in case the judgment were made of the after-images.

[23] "Über die Grenzen der Empfindlichkeit des Auges für Spectralfarben," Archiv. für Ophthalmologie, 1871, XVII, pp. 123-132.

color sensations rise to their maxima at different rates but the only statement he makes with regard to the order of rapidity of rise for the different colors is that it is the slowest for red.

(3) *Kunkel.* Three years later the problem was taken up anew by Kunkel.[24] He is also generally accredited with having used Exner's method in a modified form. The modifications made by him, however, were rather fundamental. He repudiated Exner's method in the following regards. (1) His observers were utterly unable to make the comparisons needed in terms of the after-response. And (2) he denied the possibility of determining more than a rough approximation of the time required for the sensation to reach its maximum, when equal intensities of lights were used in conjunction with a constant difference of exposure time, as is required by Exner's method. In devising his own method he begins with the assumption that the more intense is the light, the more quickly will the sensation aroused by it rise toward the maximum.[25] With this assumption as a basis two points of revision are made. (a) The lights used shall be of different intensities. One must be a great deal stronger than the other; and, if the method is to accomplish its purpose, the sensation aroused by the stronger light must, as stated above, rise more rapidly toward its maximum than the sensation aroused by the weaker light. The intervals of exposure of the two lights must be so regulated, however, that the sensation aroused by the comparison light reaches its maximum before the maximum is reached by the sensation aroused by the standard light. And (b) a variable and not a constant difference in the time of exposure to the two lights shall be employed in each series of determinations. In detail the method is as follows. The apparatus is so arranged that the exposure to the standard and comparison lights end at the same time. A given very small interval of time is chosen for the comparison light. Then a time of exposure is found for the standard light

[24] "Über die Abhängigkeit der Farbenempfindung von der Zeit," Archiv. für Physiologie (Pflüger) IX, pp. 197-220, 1874, Bd. IX, pp. 197-220.

[25] Exner had found this to be true for white light; Kunkel assumes it also for colored light. Colored light alone was used in his experiments.

which causes it just to match in apparent brightness the comparison light. This procedure is repeated for a graded series of exposure times for the comparison light. From this series the time required for the comparison light to arouse its maximum response in sensation is selected in accordance with the following principle. The exposure times of the standard light are so regulated that the sensation aroused by it would, if the stimulation were allowed to continue, reach its maximum considerably later than the sensation aroused by the comparison light. However, the stimulation by both lights is cut off before the sensation aroused by the standard light reaches its maximum. For the series of observations under consideration, then, it may safely be assumed that the longer the exposure to the standard light, the stronger is the sensation aroused by it. In order to determine the time of exposure required to arouse the maximum value of sensation, it becomes necessary, therefore, only to pick out from the series that value of sensation which is matched by the sensation aroused by the longest exposure to the standard light to be found in the series. The method can be further elucidated, perhaps, by a graphic illustration such as is given in Figure IX.

In this figure the temporal courses of the sensations aroused by the standard and comparison lights are represented by curves in

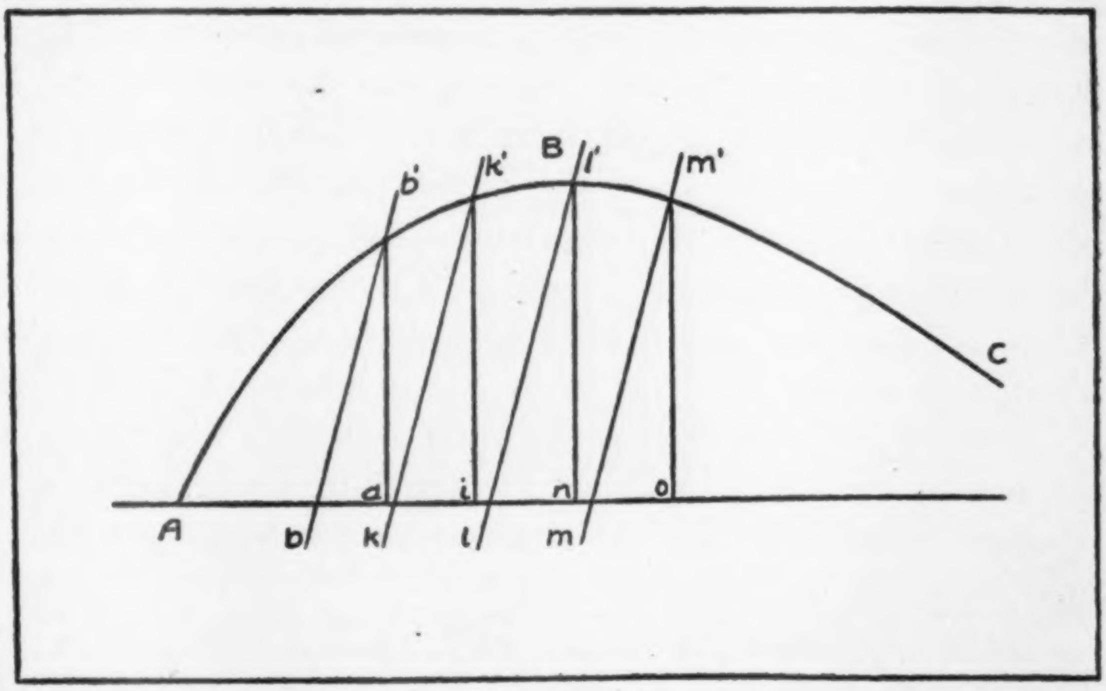

Figure IX

which the intensity of sensation is plotted against the time of exposure of the lights. The general course of the comparison sensation is represented by the curve A, B, C; the course of the standard sensation is represented by the curves bb'kk'll' and mm', the times at which the exposure of both lights is cut off, for the cases considered, by the points, d, i, n, and o; and the lengths of the exposure of the two lights, standard and comparison respectively, by the lines bd and Ad, ki and Ai, ln and An, mo and Ao. Since b', k', l', and m' are common to the two curves and are points which represent equal intensities of the two sensations, and both ki, and ln, and mo are the times of exposure required to bring the standard sensations to these values; then if in comparing the values bd, ki, ln, and mo, it is found that ln, has the greatest value but only slightly greater than ki, or Mo, An may be taken as the time required for the comparison sensation to attain its maximum. From a consideration of this method it is obvious that nothing more than a determination of the time required for a sensation to come to its maximum can be made with any degree of accuracy, although Kunkel has in a rough way plotted the rise of the visual sensations. (See Figure X.) He did this by assuming that the rise of the sensation for the more intense stimulus could be represented approximately by a straight line; and that, accordingly, the excitation caused by it may be considered proportional to the length of exposure. He also contends that the time required for a sensation to come to its maximum can be determined with more precision by his revision of the method than by the method in its original form; for, the difference in the pitch of the curves being much greater in the former than in the latter case, not so great a change in exposure time is required to make a noticeable change in sensation. That is by using lights widely different in intensity and a variable rather than a constant exposure time, he has succeeded, he believes, in giving to Exner's method a greater sensitivity than was attained in the form in which it was employed by Exner himself.

Kunkel worked with colored light alone,—a red, green and blue chosen from the spectrum. The range of wave-lengths,

however, was not specified. The spectroscope used by him was apparently not calibrated for wave-lengths and his only means of reproducing his stimulus from observation to observation was his judgment of similarity of color tone. Two intensities of lights were used for red and blue, and three for green. No specification is given of the intensities used, nor can they be determined from any data given by him. He shows his results for these intensities in the form of curves, given in Figure X.[26]

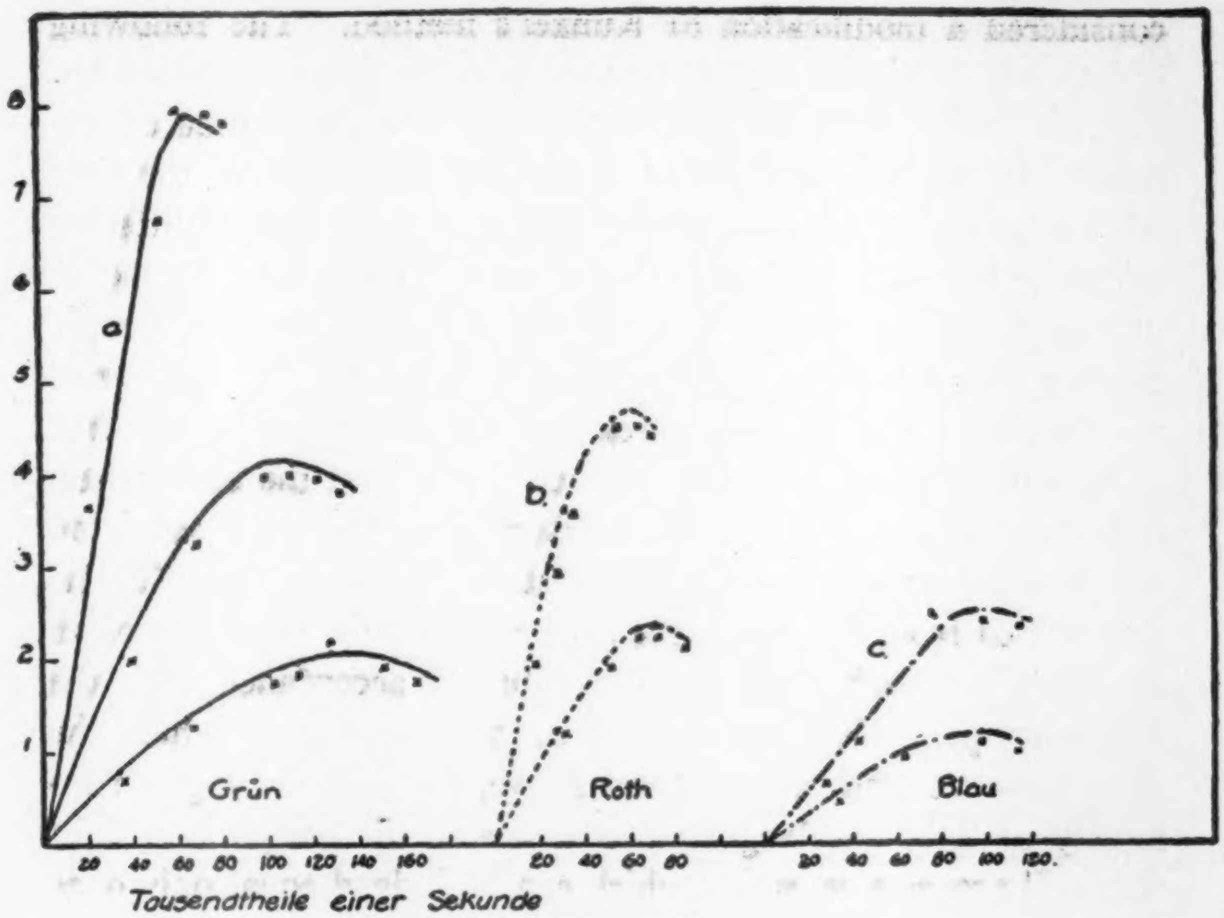

FIGURE X

A crude attempt was made to get comparative results with lights of equal brightnesses. The lights were not equated by

[26] The values shown in these curves for the visual sensation were obtained in the following manner. The light to be used as a standard was made of sufficient intensity so that its brightness might be considered to increase in direct proportion to its time of exposure. The comparison light was then rated for different exposure times in terms of the exposure time of the standard light which caused the two stimuli to be judged equal. The ordinates of the curves represent the exposure times of the standard light—plotted to an arbitrary scale.

photometric comparison, but he assumed that the green of his spectrum was twice as bright as the red and four times as bright as the blue, and made reductions of the intensity of the red and green to accord with this rough estimation.

(4) *Dürr.*[27] Unable to get satisfactory results by the methods of either Exner or Kunkel, Dürr attempted to find still another method of varying the factors involved, in a way that would suit the purpose of the problem. The method he devised may be considered a modification of Kunkel's method. The following points of similarity and difference may be noted between the two methods. Like Kunkel, Dürr used a variable time of exposure to the two lights, and a variable difference in the time of beginning these exposures. He also used lights differing widely in intensity, and made the stronger the standard, by means of which the maximum value of the sensation aroused by the weaker was detected. Unlike Kunkel, however, (1) he varied the length of the two exposures and the difference in the time of beginning these exposures in such a way that the comparison sensation became equal to the standard after the latter sensation had reached its maximum value, instead of before; and (2) he determined from his results the time required for the comparison sensation to reach its maximum value in accordance with the following principle: In a series of observations in which the variations are made as described above, there is for a given intensity of light one length of exposure to the comparison light that will arouse a sensation which can be judged equal only once in its course to the sensation aroused by the standard light, and that is the time required for the comparison light to arouse its maximum response in sensation. This principle may perhaps be made clear by a consideration of the curves shown in Figure XI.

In this figure, curve A B C, represents the intensity curve of the standard sensation, A′B′C′, the curve of the comparison sensation; and AA′, the interval of time between the beginning of the exposures of the standard and comparison lights. Were the exposures made to end at aa′, cc′ or at any other time than

[27] "Über das Ansteigen der Netzhauterregungen," Wundt Phil. Studien, 1901-1903, XVIII, pp. 215-273.

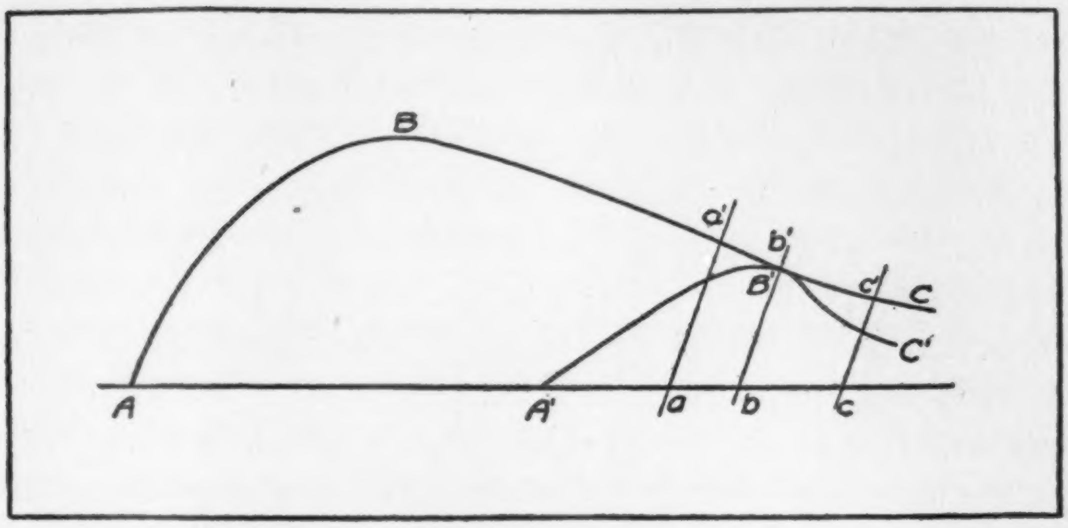

FIGURE XI

is represented by bb′, the comparison light would be judged darker than the standard. Were the time AA′ made shorter, the comparison light would never be judged equal to the standard; and were it made longer the comparison light would twice be judged equal to the standard, and a part of the time stronger and a part weaker. That is, the curve A′B′C′ would rise above the curve A B C and would cut it, therefore, in two places. This would happen also were the time AA′ to remain the same and a stronger light be used for the comparison light. How difficult the method is of a systematic application must be obvious even with this brief consideration of the possibilities. The success of the determination depends upon selecting just the right relation between the three variables,—the ratio of intensity of standard to comparison light, the time from the beginning of the first light to the beginning of the second light, and the length of exposure to the two lights. If this is not done, the curve A′B′C′ will not touch the curve A B C at one point only; and the time required for the comparison sensation to reach its maximum value cannot be determined. Our own attempts to use the method have proved very discouraging, and our verdict is that it is the least feasible of any of the methods that have yet been described.

Using the method described above Dürr obtained results which disagree with those of most other investigators. His conclusions

were threefold. (a) The time required for visual sensation to reach its maximum is independent of the intensity of the light used, (b) it is longer for colored than for white light, and (c) it is the same for all of the colors. According to his results this time is, for white light for all intensities used, approximately 0.260 seconds; and for colored lights, about 0.541 seconds. A comparison of his results with those of other investigators shows that even the few who agree with him in some points, do not agree with him in all. Swan alone concurs with him in the belief that the development-time for white light is independent of the intensity of the light used; and Swan's results, it will be remembered, were not directly determined, but computed from experiments with short exposure times. Swan worked with white light alone and found for the development-time a value of about one-half that assigned to it by Dürr. MacDougall agrees with Dürr in that he believes that colors of equal brightness rise to their maximum at the same rate; but he maintains, on the other hand, that the rate of rise sustains a direct relation to the intensity of light used. His value for the development-time is about one-fifth of that obtained by Dürr.

The radical disagreement of Dürr's results with those of other investigators who have used methods differing from his and who have not disagreed so much among themselves, leads one strongly to suspect that the disagreement is largely the result of his method of working. It was our intention to use his method along with the others for the sake of finding out more definitely whether the type of discrepancy shown in his results is characteristic of the method or a peculiarity of the observer. Because of the tediousness of the method, however, and the more or less unsystematic way in which it must be applied, our work with it was confined to one intensity and one color of light. This gave us the opportunity of comparing our results with Dürr's in one regard only, namely, the order of magnitude of the value gotten for the development-time. The effect of wave-length and intensity could not, for example, be compared. With regard to the order of magnitude of the development-time our results agreed with Dürr's. That is, the value of the development time

was much greater than was obtained by the other methods. With regard to the causes of this difference in the results obtained by Dürr and other investigators we have only the most casual suggestions to make. (1) It seemed possible that the judgment of the sensations might be influenced by the after-response and that this might lead to the overestimation of the development-time. That is, the standard light is so much stronger than the comparison light and is exposed so much longer that the tendency would be to give a much stronger positive after-effect than is given by the comparison light. Within limits the tendency to do this would possibly decrease with increase in the exposure time to both lights for the increment would doubtless have more effect on the after-response when applied to the relatively short exposure of the comparison light than to the longer exposure of the standard light; and this would exert a tendency to lessen whatever influence the difference of after-response might have on judgment.[28] However, that the after-response does in all probability influence the judgment was shown by decreasing its possibility of occurring and noting the results. This was accomplished by preventing the stimulus-light from being succeeded by the usual dark field produced by cutting off the light from the stimulus box,—a dark field being the most favorable possible for the quick development and brilliancy of the positive after-image. By means of a white mat surface fastened to the

[28] The only study of the positive after-image which the author has been able to find, where the lights and exposures employed are at all comparable with those used in the present experiment, was made by Franz in 1901, (Psy. Rev. Mon. Supp., No. 3). He gives the following data. An exposure of 1 sec. arouses a positive after-image in 100 percent of the cases, one of 1/10 sec. in 97 percent of cases; one of 1/100 sec., in 82 percent of the cases; and one of 1/1000 sec., in only 19 percent of the cases. If we can assume that the factors which affect the frequency with which the after image occurs similarly affect the intensity of those which occur, we conclude from this data that an increase in a very short exposure to the light will have more effect than an increase in a longer exposure, within the range of exposures used by Franz. We can give this assumption no other warrant, however, than its plausibility. In this same article Franz shows that the effect of decreasing the intensity of the stimulus is to produce at first a slow and later a more rapid decrease in the frequency with which after-images occur. This fact will be referred to later in another connection.

exposure disc with its forward edge flush with the edge of the closed sector which cuts off the stimulus light and a small electric lamp the circuit of which was closed at the instant the stimulus light was cut off, the stimulus surface and the interior of the stimulus box was illuminated by white light immediately succeeding the cutting off of the stimulus light. That is, the disappearance of the stimulus was followed by a light rather than a dark field and the positive after-image was not given an opportunity to develop. The effect of this was to lessen very much the determination made of the development-time, and to bring it more nearly into agreement, therefore, with the values obtained by other methods. (2) From the ratios given by Dürr of the intensities of his comparison and standard lights it seems hardly possible that the two could have been judged equal at the end of the time given by Dürr. That is, this ratio was 27 to 4, for example, in one case, and 23 to 4 in another. The time for which the standard light was exposed in each case was about 1.7 seconds. For the comparison light to have been judged equal to it would have necessitated that the intensity of the sensation aroused by the standard light must have as a result of adaptation or exhaustion sunk in less than 2 seconds to a value equal to that given by a light of approximately one sixth or one seventh its intensity. From all that is known of the rate of loss of sensitivity due to exhaustion this seems hardly possible. There is, of course, the possibility that in the adaptation or exhaustion experiments which in most cases have not been done in connection with experiments for the determination of the development-time, account has not been taken of the rapid fall in intensity that occurs just after the maximum time has been reached, and that, this loss, due to exhaustion in a given interval of time, has therefore been underestimated. Such a possibility is, however, ruled out by the results of Broca and Sulzer (See Fig. III) and of the author using the method employed by them (see Table VIII and Fig. XIII). Remembering that the adaptation-time of Broca and Sulzer to the standard light was at least two seconds and that the author's adaptation time was six seconds, it will be seen that here we never have a loss due to

exhaustion for two or six seconds greater than that given by decreasing the light one half, except perhaps in the case of blue and white for the highest intensity of light used. (3) Dürr does not give a specification of his lights, either photometrical or radiometrical; apparently, however, the comparison lights used by Dürr were of very low intensity. We judge this to be the case from two facts: (a) the large ratio between the standard and comparison lights, and (b) his statement that the comparison lights were of such low intensities that there was not enough color present to make the photometric comparison with a white light difficult by the equality of brightness method. Whether or not the low intensity of the comparison light sustains any causal relation to the difference in the results obtained by him as compared with others we are not at present able to state. It can be affirmed, however, that the very low intensities of his comparison lights and the high intensities of his standard lights would affect the relative rate at which the curve A′B′C′, after its highest point has been reached, falls away from the curve A B C. This should have a bearing at least on the sensitivity of the method, for if the maximum point is to be located with precision, curve A′B′C′ should after its brightest point has been reached fall away sharply from ABC for upon this difference depends the amount by which the exposure time must be changed before the comparison sensation becomes noticeably less intensive than the standard sensation.

(5) *MacDougall.* So far the methods discussed have conformed to two general types,—the method of direct comparison or equality of brightness, and the method of Exner with its modifications by Kunkel and Dürr. MacDougall[29] in 1904 introduces a third type. Like Exner's his method may be classed as an indirect method, and was used only for finding one point in the intensity curve, namely, the point of maximum intensity. It differs from Exner's method, however, not only in the means of detecting the point of maximum intensity, but in the manner of making the judgment.

[29]"The Variation of the Intensity of Visual Sensations with the Duration of the Stimulus." British Journal of Psychology, 1904, I, pp. 151-189.

MacDougall gives two reasons for attempting to modify the manner of making the judgment. The first is a wish to avoid the effect of the contrast which is present between stimuli simultaneously presented. It is difficult, however, to get his point of view in this regard, for the only effect of simultaneous contrast is to increase the sensitivity of the judgment and therefore to lower the actual amount of change that is needed in the stimulus to produce a just noticeable change in sensation. That is, since stimulus A differs from stimulus B only in brightness not in color value the only chance for contrast will be in the brightness aspect of the sensation. The effect, therefore, will be only to increase the effect on sensation of whatever difference there is in the stimulus and thus render small changes more readily detectable. In fact, it is just this condition that is striven for in the construction of the better class of photometer heads in order to increase the precision and sensitivity of the judgment. The evolution of the photometer head for the equality of brightness method has in fact consisted largely of the development of this feature alone. In this connection, compare, for example, the precision and accuracy of judgment with the type of head used in the Rumford photometer, in which the fields judged are so widely separated as to be removed from all contrast effect on each other, with that of the most modern type of Lummer-Brodhun photometer, in which the fields to be judged are so arranged as to give a maximum of contrast effect of the two fields on each other. MacDougall's second reason for wanting to change the method of making the judgment was because of his belief that it was unnecessarily difficult. The judgment of two stimuli simultaneously presented for so short a time he thought could be made with less accuracy than if the stimuli were presented successively at a favorable rate for a number of times. His apparatus for carrying out this method of making the judgments consisted of a large wooden disc with open sectors diametrically opposed to each other, the size of which could be varied independently to stimulate the eye for different lengths of time. This disc was rotated in front of a milk glass plate which was uniformly illuminated and gave the stimuli used in making the de-

terminations. During one rotation of the disc the eye was thus exposed to the illuminated plate twice, each exposure being for the length of time required respectively for one open sector to pass in front of the plate. The eye thus received in alternation the two stimuli, and the presentation was continued until a satisfactory judgment could be made. Two criticisms, perhaps, may be passed on this method of presenting the stimuli. (a) By giving the stimuli in succession rather than simultaneously a time error was involved which could be reduced, of course, by increasing the rapidity with which the stimuli were presented; but (b) if the stimuli were given in rapid succession it would scarcely be probable that each excitation would be uninfluenced by the preceding excitation. There are two ways in which this influence might be exerted. (1) The after-effect, positive or negative, depending upon the interval between the successive exposures, might modify the effect of the succeeding exposures; and (2) the lag in the response might itself be modified by a repetition of exposures to the same stimuli either through the carrying over of the excitation from impression to impression or by increasing the excitability of the light-sensitive structures. MacDougall's method of determining the point of maximum sensation is as follows. One of the open sectors was made of such a breadth that, with the speed of rotation used, the time of exposure of the eye to the illuminated plate was less than was required to arouse the maximum response. The width of the other sector was then made enough greater than the first to produce a just noticeable difference in sensation. Next the width of the second sector was made the standard and the width of the first was increased until a just noticeable change was produced. This alternative use of the two sectors as standard and comparison, was continued until the maximum was reached. So long as the time of exposure to each was less than is required to arouse the maximum response in sensation, the comparison sensation was judged more intense than the standard. When this time had been reached for the standard and exceeded by the comparison, the comparison was judged darker than the standard. The method thus affords the possibility of detecting the time re-

quired to arouse the maximum response in sensation within the limits of change required to produce a just noticeable difference in sensation. MacDougall's method of grouping the judgments for the purpose of detecting the maximum is obviously much superior to his method of presenting the stimuli for the individual judgments.

From the results of his experiments MacDougall concludes that the time required for white light to arouse its maximum response varies directly with the intensity of the light used; and that colored lights of equal photometric value all require the same time to produce their maximum effect in sensation.

C. *Recapitulation.* It has long been recognized that the visual sensation does not come at once to its maximum value. The fact was noted by Bacon in 1711, by Beudant in 1815, by Plateau in 1834, and by Swan in 1849; but it was not until the experiments of Exner in 1868, that the work of determining the development-time of visual sensation was definitely begun. Various methods have been used by different investigators and different results have been obtained. As stated in the introductory chapter, this is one of the reasons that has induced us to take up the problem anew. In general two classes of methods have been used, the direct and the indirect. Under the first class may be included the methods used by Swan, Charpentier, Lough, Broca and Sulzer, Martius, Büchner, and Berliner; and under the second, the methods of Exner, Lamansky, Kunkel, Dürr, and MacDougall. No two of these methods have been the same in all essential details and little, if any, systematic attention has been given by the individual investigators to a comparative study of methods. Moreover, the control and specification of conditions has not been such that a comparison can be made from their published works. Without further experimental work, then, a decision is impossible between the conflicting results that have been obtained. The chief points of interest in the earlier investigations have been as follows,—(1) A comparison of the times required for the different color sensations to reach their maximum; (2) a comparison of this time with the time required for colorless sensation; and (3) a determination of the effect of

the intensity of the light on the time required for a sensation to reach its maximum. With regard to these points there has been the widest disagreement, especially with regard to the first. Kunkel, Lamansky, Broca and Sulzer, and Martius, for example, found that the different sensations of color require different lengths of time to reach their maximum; while MacDougall, Dürr, and Berliner concluded that the development time is independent of the color value of the sensation. Furthermore, with regard to this point a great deal of disagreement in detail is found even among those who have agreed on the more general aspect of the question. That is, while Dürr, Berliner, and MacDougall agree that all the colors come to their maximum in the same length of time, they disagree with regard to the value which should be assigned to that time; and while Kunkel, Lamansky, Broca and Sulzer, and Martius agree that the colors all require different lengths of time to reach their maximum, they disagree both with regard to the length of time which is required and to the order in which the colors should be placed with regard to the time that is required. Only the last of these points of disagreement, the order of rapidity with which the colors came to their maximum, will be considered here. For a detailed comparison of the individual value of the time required the reader is referred to Table VI. For Kunkel red produced its maximum effect in sensation the most quickly, blue next, and green the least quickly; for Lamańsky red was the slowest of the three to come to its maximum; and for Broca and Sulzer the order from fastest to slowest was blue, green, and red. In the work of Broca and Sulzer alone, the colors were equated in brightness. For the others with the exception of Martius, not even a rating of the colors in order of brightness can be given. Martius' colors' from lightest to darkest were yellow, green, blue and red.

The four men who have worked both with white and colored lights have agreed that there is a characteristic difference in the time required for the two kinds of light to produce their maximum effect in sensation. Again, however, there is quite a wide disagreement with regard to what value should be assigned to this difference. Dürr found, for example, that colored light re-

quires approximately twice as long to produce its maximum effect in sensation as white light; for MacDougall and Martius the time which is required for a colored light to produce its maximum effect lies within the range of values obtained for the different intensities of white light used, and for Broca and Sulzer, the time required for white light to arouse its maximum response is longer than for blue, and shorter than for red and green. A fair comparison, however, cannot be made from the results obtained by Martius, Dürr, and MacDougall because they have made no attempt to specify the intensities of their colored lights.

Concerning the last point mentioned above there is more agreement than for the other two. Dürr alone of those who have made the determinations of the time required for the sensation to reach its maximum, has found that the time is independent of the intensity of light used. For white light his results are contradicted by those of Exner, Broca and Sulzer, Martius, MacDougall, Charpentier, Lough, and Berliner; and for colored light by those of Kunkel, Broca and Sulzer, and MacDougall. Swan alone agrees with him, and Swan, it will be remembered, came to his conclusions only from some rough experiments with reference to the effect of short exposures on the eye's response. The experimental determination of the time required for the sensation to reach its maximum was not made by him nor was systematic work done for times of exposure shorter than this.

In order to bring all the foregoing facts into a briefer compass for the sake of a more ready comparison Table VI has been compiled. This table shows the range of work covered by each investigator and within what limits the results obtained vary.

TABLE VI

Showing the results obtained by previous investigators for the time required for sensation to reach its maximum value.

	Sensation	Stimulus	Wave-length specifications	Intensity specifications	Time required for sensation to reach its maximum value (seconds)
Exner 1868	White	White paper		Unit is light reflected from white paper illuminated by oil lamp	
				1 unit	0.150
				1/2 "	0.200
				1/4 "	0.246
				1/8 "	0.287
Kunkel 1874	Colors	Spectrum	None	Prismatic spectrum of a petroleum lamp	
	Red			No reduction in intensity	0.057
	Green				0.097
	Blue				0.101
	Green			Intensity decreased one-half	0.133
	Blue			Intensity doubled	0.091
Charpentier 1887	White	White paper illuminated by skylight		Five intensities in arbitrary scale used	0.014-0.049
Lough 1896	White	White paper illuminated by a 1 cp. lamp			
				0.097 meter-candles	0.148
				0.388 "	0.110
				1.552 "	0.100
				6.208 "	0.085
				24.832 "	0.090
Dürr 1902	White	Milk glass illuminated by carbon lamp filters		Two intensities Values not given	0.266
	Colors				
	Red		700-610$\mu\mu$	Two intensities	
	Yellow		Not given	"	
	Green		510-486$\mu\mu$	"	0.541
	Blue		476-440$\mu\mu$	"	

Table VI (continued)

	Sensation	*Stimulus*	*Wave-length specifications*	*Intensity specifications*	*Time required for sensation to reach its maximum value (seconds)*	
Martius 1902	White	White paper illuminated by an arc lamp		Ratios in an arbitrary scale		
				1	0.013	
				1/2	0.039	
				1/4	0.053	
				1/8	0.066	
				1/16	0.078	
				1/32	0.093	
	Colors	Colored glass and gelatines	None	Order of brightness of colors: Yellow, Green, Blue, Red		
	Yellow				0.020	
	Blue				0.036	
	Green				0.048	
	Red				0.090	
					Obs. I	Obs. II
Broca and Sulzer 1903	White	White paper illuminated by an arc lamp		170 meter-candles	0.040	0.030
				126 " "	0.065	0.035
				885 " "	0.065	0.050
				64.5 " "	0.125	0.050
				42.5 " "	0.125	0.070
				32.4 " "	0.150	0.070
				21.0 " "	0.150	0.125
				16.2 " "	0.200	0.125
	Colors	Filters	None	See figure III	See figure III	

TABLE VI (continued)

	Sensation	Stimulus	Wave-length specifications	Intensity specifications	Time required for sensation to reach its maximum value (seconds)
McDougall 1904	White	Milk glass illuminated by lamp		Ratios in arbitrary units	
				1	0.049
				1/2	0.055
				1/4	0.061
				1/8	0.066
				1/16	0.078
				1/32	0.089
				1/64	0.100
				1/128	0.127
				1/256	0.142
				1/512	0.150
				1/1024	0.183
				1/2048	0.200
	Colors	Gelatines	None	Equal in brightness Three intensities Value not given	Same for all colors 0.100-0.142
Büchner 1906	White	Milk glass illuminated by lamp		0.027 meter-candles	0.230
				0.145 "	0.200
				0.260 "	0.120
Berliner 1907	Colors	Papers and gelatines	None	None	Same for all colors 0.300

III. EXPERIMENTAL

A. *Purpose of Investigation*

As stated in our introductory chapter the plan of this investigation includes the following points. (1) An experimental examination of the older types of method will be conducted, to find out which have sufficient feasibility and precision, to warrant their further use in connection with our work on the problem. (2) A comparative determination of the relative lag of colored and colorless sensation with lights of the same photometric value, for the same observers, under the same experimental conditions will be made by the methods selected. And (3) the determination will be made by three new methods. By this plan it is hoped that the following objects will be accomplished. (a) Not only will more accurate knowledge be gained of the time required for the visual sensations to come to their maximum, but a comparison of values will be made during the course of their rise. (b) Data will be obtained which are directly applicable to photometric methods in the interest of which primarily the study was undertaken. And (c) through the intercomparison of methods with the same observer and under the same experimental conditions a selection will be made of those which combine the following features: logical sureness, precision, and convenience and feasibility of application.[30]

[30] For example, in studying the conditions which decrease the power of the eye to sustain clear seeing under different lighting conditions two factors should be taken into account,—the depression of retinal functioning, and the depression of muscular functioning. (For a description of tests for depression of muscular functioning, see C. E. Ferree: "Transactions of the Illuminating Engineering Society," 1913, VIII, pp. 40-60. Also C. E. Ferree and G. Rand, ibid, 1915, X, pp. 410-413 and 454-491; 1916, XI, pp. 1122-1130.)

A depression of retinal functioning may show itself in any or in all of the following ways: (1) A lessening in sensitivity to colored or colorless lights as tested by the momentary responses; (2) an increased susceptibility to exhaustion or fatigue; (3) a decreased rate of recovery from fatigue; and (4) an increased inertia or lag in giving the maximum response.

B. *New Methods of Making the Determination*

The new methods which are being presented here for the first time, are designed not only to ascertain the time in which a given stimulus produces its maximum effect in sensation, but also to make possible a comparison of the effects produced at different times before the maximum effect is attained. There are two possibilities of making accurate and reproducible judgments of sensation, namely, the judgments of equality and of just noticeable difference. Upon these judgments must all quantitative work in psychology ultimately rest. Both of them have been utilized in the development of the methods mentioned above. The development of these methods has in fact been just the systematic application of these two judgments to the problem in question, in accord with the purposes mentioned at the beginning of the paragraph.

(1) *Method 1.*[31] This is a direct method and from its similarity to the photometric method of the same name it may be called a direct comparison, or equality of brightness method. The principal feature of this method is to establish a series of standard sensations graded in brightness to which the sensation whose temporal course is under investigation may be matched at various points in its rise to the maximum. In a previous chapter we have pointed out that Broca and Sulzer, Büchner, Lough, Berliner, Charpentier, and Martius failed to provide such a series of standard sensations graded in brightness and have indicated in each case wherein the deficiency lay. Obviously such a standard may be obtained by establishing a reproducible series of just noticeable differences in sensation for the same wave-lengths of light that arouse the sensation whose development is to be

Tests covering the first three of the above points are already in use in this laboratory. It would add materially to the completeness of our equipment for this work, if a method which is sufficiently brief and convenient in application to suit the purposes of a laboratory test, could be found for the fourth point.

Up to this time, we regret to say, our use of the older methods has been attended with somewhat discouraging results.

[31] For the suggestion of Method 1 and Method 2 the author is indebted to Dr. Ferree.

investigated. This series should begin at zero and rise to a value as high at least as the maximum for the sensation under investigation.

Before going further into the details of this new application of the equality of brightness judgment to the work of determining lag a word of general perspective may not be out of place even at the risk of involving repetition. As we have pointed out in the preceding chapter, the difference in the problems to which this judgment is applied when it is based on making a photometric comparison of two light intensities and when it is used in detecting the lag in sensation, should be kept clearly in mind. In the former case the eye is exposed to the standard and comparison lights for equal intervals of time and therefore no account need be taken of the changing effect on sensation of different lengths of exposure. In the latter case the eye must be exposed to the standard and comparison lights for different intervals of time, and the changing effect on sensation of different lengths of exposure is of great importance. In the former case, too, sensations are matched with the object of equalizing light intensities and of giving a relative rating of the two light sources; in the latter, the problem ends with the matching of the comparison to the standard sensation. In some respects the problem in the latter case is essentially simpler than in the former for a rating of light sources in terms of their power to arouse equal sensation values at the photometer screen is not required. It is more complicated, however, in that, if the brightness of sensations aroused by different lengths of exposure to the comparison light are to be compared, the sensation aroused by the standard light must have a definite place in a graded series. That is, if the sensations aroused by the comparison light are to be graded from minimum to maximum, the method must provide a series of standard sensations graded in brightness to which the comparison sensation for the different lengths of exposure may be matched. In the use of this method by previous investigators, as we have already noted, such a series of graded standard sensations has not been provided. In their work the rating of the comparison sensation was in terms of a series of

standard stimuli and a proportional rating was assumed for the sensations aroused by these stimuli, in spite of the fact that in some of the cases the eye was exposed for different lengths of time to the standard stimulus and in all cases no account was taken of the comparative rates of exhaustion of the eye to light of different intensities and of different wave-lengths. It is in fact for the purpose of establishing directly a series of standard sensations, graded in brightness and obtained with a standard time of exposure, that we have taken up the method anew. In establishing this series the rating will be made directly in terms of sensation. It will not be assumed from intensity relations existing between the stimuli as has been done in previous work, in which in one case at least the decay of sensation was disregarded altogether (Broca and Sulzer), and in all of the others no account was taken of the variability in the rate of decay with lights of different intensities. Obviously the just noticeable difference series, previously mentioned, should furnish the standard needed. This series should be for the same wave-lengths of light which are used to arouse the comparison sensation, and should begin at zero and rise to a value as high at least as the maximum of the sensation whose development is under investigation. How such a series may be established, will be understood better in detail when we come to a description of the apparatus. It will be sufficient to say at this point only the following. Two contiguous comparison surfaces are provided, either of which may be illuminated by the standard light in slightly varying amounts. In the beginning, for example, surface 1 is dark and surface 2 is illuminated until it is just noticeably lighter than surface 1. Surface 2 is then made the standard and the light is increased on surface 1, until it is just noticeably lighter than surface 2; and so on, until the desired number of just noticeably different brightnesses are obtained. In each case a record must be kept of the precise amount of light used for each member of the series, and of the lengh of time of exposure which should preferably be kept constant. In the following experiments the first of these requirements was attained by means of a double micrometer slit, adjustable to thousandths of a millimeter, which was placed in the

end of the collimating tube of the spectroscope. A very important feature of the method is, of course, some means of guaranteeing the reproducibility of the series of standard sensations.[32] This we believe can be done for a practised observer within the limits of certainty that are accepted in making many physical determinations. For example, the sensitivity of a delicate galvanometer (of the Paschen type, for example), may vary from day to day and for this reason a check is made on its sensitivity prior to the measurement of an unknown current. That is, the instrument is provided with a sensitivity tester and tests are made as the need of the work requires. This can be done also for the eye. That is, like the galvanometer, if the sensitivity of the eye varies from day to day, its scale of responses will vary correspondingly, but just as a check may be had on the sensitivity of the galvanometer, so may it be had on the eye.[33] This may be accomplished in the following way. As a preparation for the work the just noticeable difference series should be determined until a high degree of reproducibility is obtained from series to series. When a satisfactory degree of practice is reached it will probably be sufficient prior to a given experiment to conduct a brief test to see that the sensitivity of the eye of the observer has not changed. This would probably consist of a test of the scale at only one or two points. One is usually considered sufficient in the case of a galvanometer, for example, but, if this is not sufficient, it does not take long for a practised observer to run over the whole scale. This has the advantage that, if the sen-

[32] The accumulated error through a series with a practised observer has never amounted to a just noticeable difference. For example, an intensity of stimulus which has at times given eight just noticeable differences of sensation has never at another time given seven or nine just noticeable differences. That is, the points in the sensation and stimulus series may vary from sitting to sitting but never as much as is represented by a just noticeable difference in sensation.

[33] It should not be understood that we wish to carry this analogy too far. If, for example, the sensitivity of the galvanometer changes from day to day, a corrective factor can be determined and applied to convert the variable deflections into some value taken as a standard. The correction of the eyes to a standard sensitivity can not, of course, be done, as yet. All that can be done, is to refrain from working when the test shows a significant change in the eye's sensitivity.

sitivity of the eye has changed, a new scale of sensitivity is established which can be used for that particular time and experiment. With a practised observer and the proper control of conditions we have found so little variation in the series from time to time that the check provided by the briefer test has been amply sufficient.

Once the standard series of sensation is established the points in the rise of the comparison sensation to its maximum may be determined in either of the following ways. (1) The standard series may be reproduced, point by point, and the exposure time of the comparison light be adjusted until the sensation aroused just matches the standard sensation; or (2) the inverse of this procedure may be used. That is, different exposure times may be selected for the comparison light and a member be selected from the standard series which matches it. In either way the resulting values of the sensations aroused by different intervals of exposure of the comparison light may be rated within a limit of accuracy which falls at any point within a just noticeable difference of sensation. The method permits then of placing in a just noticeable difference series the sensation aroused by exposing the eye to a given intensity and composition of light for different intervals of time. It also permits us to compare in case of lights of different composition the intervals of exposure required to give us the third, fourth, etc., just noticeable difference in the brightness scale; and, if we are allowed to assume that brightness values which are three, etc., just noticeable differences removed from zero are equal, we should be able to detrmine what lengths of exposure for the different wave-lengths of light are required to produce equal sensation values. Repeated trials have lead us to believe that this assumption is in most cases justifiable. That is, repeated trials have shown that a sensation of any color, built up by getting three just noticeable differences from zero matches in brightness the sensation of another color, also built up by getting the third just noticeable difference from its zero.

(2) *Method 2.* This may be classed as an indirect method and rests on the fundamental assumption that the more intense a sensation is, the greater will be the number of just noticeable

differences between it and the zero sensation. That is, considering the principle in relation to the determination of the time required for a sensation to reach its maximum brightness, we would assume that the time of exposure which would give the greatest number of just noticeable changes in brightness for a stimulus of a given value, is the interval which would cause that light to arouse its maximum brightness response in sensation. In this method, a series of just noticeable differences is made for the appropriate range of time of exposure. In each series of measurements the time of exposure is kept constant; and the stimulus is varied from the zero value to the intensity of light under investigation and the number of just noticeable changes in brightness is determined. The time of exposure which gives the greatest number of just noticeable changes in brightness for a given intensity of light, is considered to be the time most favorable for light of that intensity; in other words, the time which just allows the sensation to reach its maximum brightness. Besides determining for us the time of exposure which gives us the maximum brightness the method also provides a means of rating the sensation values for different times of exposure in terms of just noticeable differences from the zero value. It allows, therefore, an opportunity for an inter-comparison among the colors of the effect of time of exposure on the brightness value of the sensation. The comparison is made in terms of just noticeable differences from the zero values. For example, from the results we may determine what lengths of exposure give sensations which represent an equal number of just noticeable brightness changes from the zero value; or what is perhaps less sure logically, the relative rating of the different color-sensations for equal times of exposure in terms of just noticeable changes from the zero value of sensation.

(3) *Method 3.*[34] With a logical sureness and accuracy equal to any of the longer methods described above, this method combines much greater ease and convenience of application. The length of time required to make the determinations and the ease with which they may be made, renders it in fact feasible as a

[34] For the suggestion of this method the author is indebted to Dr. Rand.

practical laboratory test for changes in retinal functioning (See this paper, p. 44). As was the case in Method 2, the judgments made are of just noticeable changes in sensation; but the changes are produced by varying the time of exposure, instead of the intensity of the stimulus. Consequently, just as the former might be called an intensity just noticeable difference method, so might this be called a time just noticeable difference method. That is, in this method, the just noticeable changes in terms of which the sensation is graded in its rise to the maximum, are produced directly by varying the time of exposure. The series is started with a zero value of time of exposure to the light in question, as standard; and the time of exposure of the comparison light is varied, until a just noticeable sensation is produced. This is then made the standard for the next observation, and the time of exposure of the first light is varied until the sensation produced is just noticeably brighter than the standard. So long as the comparison is brighter than the standard, it is obvious that the maximum response in sensation has not been reached. When it has been reached, the standard and comparison are judged equal; and, when it has been exceeded, the comparison is judged darker than the standard. From the results obtained by the series the following points may be determined,—(a) the time required for the stimulus light to arouse its maximum effect within the limits of a just noticeable difference; (b) the relative values of the sensation in a just noticeable difference series, as it rises to its maximum; and (c) a comparison of the intervals of exposure required for lights of different color to arouse sensations representing an equal number of just noticeable changes in brightness from the zero of sensation. If only the time required to give the maximum response is wanted, the series may be abbreviated. That is, it may not be started at the zero value; but at some point above this, safely below the point of maximum sensation. This abbreviation would lessen a great deal the labor involved in making the test and would give as a result probably all that need be known to make the test meet the practical purposes mentioned at the beginning of this section. So modified, this test is the shortest and most feasible of any that we have as yet been able to devise.

C. *Apparatus*

It is obvious that in order to use all of the methods described above, we must be able to produce two stimuli, independently variable in intensity, identical in composition, and for color work as nearly homogeneous in wave-length as is possible. We must also be able to present these stimuli to contiguous parts of the retina and to vary their periods of exposure independently by known amounts and within wide limits. The description of the apparatus which was adopted as best suited for the carrying out of these methods naturally divides itself into two parts,—(1) the apparatus for obtaining the two stimuli and varying their intensity; and (2) the apparatus for presenting the stimuli to the eye and for controlling the time of exposure.

The apparatus used for obtaining the two monochromatic lights and for varying their intensity independently and by known amounts has been used for several years in this laboratory for work on the color sensitivity of the retina. The apparatus for presenting these lights to the eye and controlling the time of exposure was designed especially for this work.

In order that the detailed description which will follow may be better understood, it has been thought advisable, first, to trace schematically the course of the ray of light from the Nernst filament, which serves as a source, to the eye of the observer. This has been done in Figure XII.

The light from the Nernst filament (N) passes through the double slit (S_1) and is rendered parallel by the collimating lens (L_1). It then passes through the carbon bisulphide prism (P), and the lens (L_2) focuses the resulting spectrum in the plane of the analysing slit (S_2). The monochromatic light emerging from this slit is focused by lens (L_3) in the plane of the disc (D). Spreading from the plane of this disc, the light is again focused by the lens (L_4) forming an image of the analysing slit (S_2) on a mat white surface at the back of the box (B). This image is observed through a tube (T_3) at the opposite end of the box.

(1) *Apparatus for Obtaining the Stimuli and Varying their*

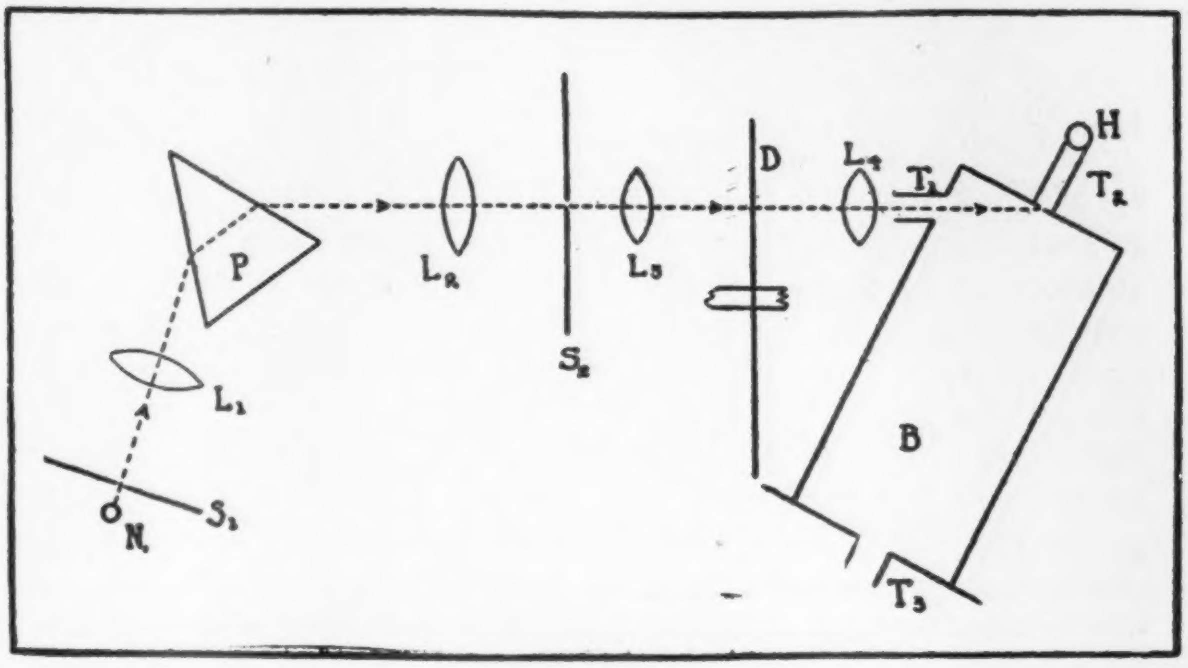

FIGURE XII

Intensity. The apparatus for obtaining the two stimuli and varying their intensities has already been described.[35] A part of this description may be quoted here:

(a) "*The Source of Light*.—The requirements of a source for our purpose are (a) that it should give a light in which all the wave-lengths are represented in sufficient strength both for the needs of the investigation of color sensitivity and for radiometric standardization; and (b) that the light emitted shall be as constant as possible in intensity and spectro-radiometric composition. After trying many light sources we have finally adopted as best for our purpose the Nernst filament. This filament, after having been properly seasoned, gives a light which changes comparatively little through long intervals of time. It has the advantage, moreover, that its shape well adapts it for use with the slit of the spectroscope,[36] *i.e.*, the shape is such as to make it possible to utilize for the illumination of the face of the prism a relatively large proportion of the light emitted. Also by increasing the length of the filament and collimator slit, it is possible to increase in direct ratio the amount of light falling on the face of the prism. When in use, in order that no light shall

[35] C. E. Ferree and G. Rand: "A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral," Journal of Experimental Psychology, 1916, I, pp. 247-283.

[36] The filament is supported by two stiff wires extending out from the lamp socket and when in use is as nearly as possible in the plane of the slit.

be lost in passing through one or more condensing lenses, the filament is mounted as closely as possible to the jaws of the slit. The filament is mounted in a lamp socket fastened to an upright. In order that the height of the filament shall be adjustable this upright consists of a short rod sliding in a tube fitted with collar and set screw which permits of a movement of the socket up and down, also to right and left. The upright is fastened to the horizontal support, extending out from the collimator arm of the spectroscope by a clamp and set screw which permits of the motion of the socket to right and left and to and from the collimator slit. The Nernst filament used by us is designed to be operated at 110 volts on a D. C. current, and has a carrying capacity rated at 1.2 amperes. When operated at its maximum capacity on a direct current, we have found, however, that the life of the filament is short. Satisfactory results have been obtained by us only when it is operated at or below 0.6 amperes. In series with the ballast, therefore, which is ordinarily used for the reduction of the current from the line and to compensate for the change in the resistance of the Nernst material as its temperature varies, we have found it necessary to use additional resistance. This resistance is needed not only to cut down the current to the desired value, but to correct for fluctuations in the line. Two coils are employed, one coarse and one fine. The former is used to cut down the current to approximately the desired value, and the latter to correct for the fluctuations in the line. Both are in the form of adjustable rheostats. The second is of special construction to give the small changes needed. It consists of a cylindrical coil of wire wound on an insulated core of brass tubing and is operated by a screw motion in such a way as to give the effect of a slider on a single wire. This rheostat is described in greater detail on p. 275. It is not on the market but can readily be constructed to order by a laboratory mechanician. The finely graduated control afforded by it not only makes it possible to correct for fluctuations in the line, as is stated above, but also to compensate for the slow decrease in the carrying capacity of the Nernst material with use. The current consumed is measured by a Weston ammeter graduated to 0.02 amperes. Operated with this type of control the light flux obtained from the Nernst may be kept constant within the limit of change that can be detected either by the radiometer or the eye.

(b) "*The Spectroscope.*—In addition to the usual features attaching to a good spectroscope, our instrument was designed

especially to meet the following needs. (1) To answer all the purposes for which a source of colored light may be used in the investigation of color sensitivity, a wide range of intensity is needed. In order too that an adequate radiometric standardization be made, it is especially desirable that light of high intensity be available. (2) If the spectroscope is to be used in conjunction with a campimeter, it is necessary that the objective arm remain in a fixed relation to the stimulus-opening of the campimeter screen and that some convenient and accurate means be had of changing the wave-lengths without changing the position of the objective. The first of the needs was met by employing a colimator slit long enough to admit the amount of light needed, and a prism and lenses large enough to take care properly of the amount of light admitted. The second point has been met by us in the two following ways, one of which is technically more correct perhaps than the other. (a) The spectroscope was mounted on a stationary base supported by levelling screws. In fixed relation to this base a slit was permanently mounted to separate out the wave-lengths which are to fall on the stimulus-opening in the campimeter screen. In order to be able to change the wave-length of the light falling on the slit the stationary base carries a track along which the whole spectroscope may be shifted by very small amounts. This movement is made by means of a screw of fine thread turned by a wheel 4½ inches in diameter. This track and the base of the spectroscope carry a Vernier scale graduated to 1/50 of a mm. by means of which any previous setting may be accurately reproduced, and in terms of the readings of which the spectroscope may be calibrated in wave-length. This method of changing wave-length not only provides abundantly for small changes in wave-length but it obviates any necessity for readjustment of the collimator arm which would be the case were the wave-lengths changed, for example, by rotating the prism. In case the wave-length is changed by this device, the prism is set for minimum deviation for the D-line, and this adjustment is kept throughout. An adjustment which gives minimum deviation for the D-line alone is generally considered by spectroscopists to be adequate for the work in the visible spectrum when the light is passed through only one prism. Kayser, for example, says:[37] 'Bei den Apparaten mit nur einem Prisma verzichtet man für gewöhnlich darauf, alle Wellenlängen unter dem Minimum zu beobachten, sondern stellt das Prisma fest auf, so dass etwa die D-Linien unter dem Minimum durch-

[37] Handbuch der Spectroscope, I, p. 510.

gehen. Die Dispersion ist bei einem Prisma so gering, dass dies gewöhnlich genügt. Das ist a ber nicht mehr der Fall, wenn man über die Grenzen das sichtbaren Spectrums hinausgeht, und so hat vielleicht suerst Langley bei seiner Untersuchung des ultrarothen Theiles des Sonnenspectrums an einem Apparat mit einem prisma eine Vorrichtung beschrie ben, welche automatisch das Minimum erhält, und welche wegen ihrer Einfachheit seitdem oft verwandt wird.' (b) In order that minimum deviation may be had automatically for all wave-lengths falling on our analyzing slit, one of our spectroscopes was built with a minimum deviation attachment. A schematic representation of this attachment and the prism in position for use is shown in Fig. 4. In

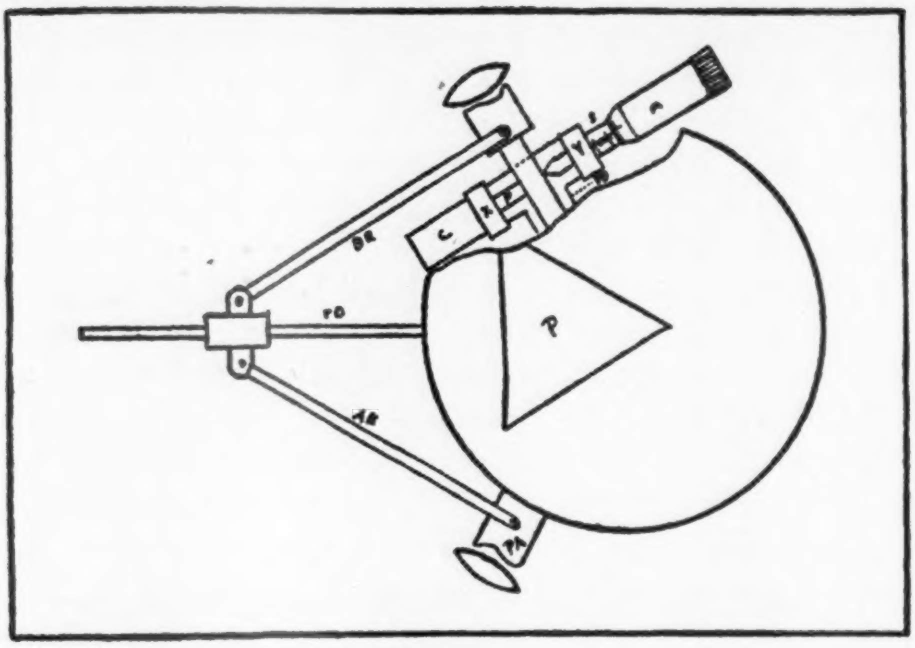

FIGURE 4

this figure, P represents the prism so placed on the prism table that its refracting angle is bisected by one of the radii of the table; PB and PA represent respectively the collimator and objective arms which are fastened to the stem of the spectroscope independent of the prism table; TD represents an arm fastened to the prism table in suich a position as to be continuous with the radius of the table which bisects the refracting angle of the prism; AE and BE represent two rods of equal length which connect PA and PB at points equidistant from the center of the table to a collar which is free to play back and forth along the arm TD. M is a micrometer screw with a graduated cylindrical head, which is used to move the collimator arm through the small angles needed to give the change of wave-length. Opposed to this screw is a plunger *p* working against the spring in the case C. When the screw advances it moves the collimator arm for-

ward and when it recedes the collimator arm is made to follow it by the push of the plunger *p*. The screw and plunger are supported by a curved arm coming off from the stem of the spectroscope, which can be clamped rigidly in any position which may be desired. This arm ends in two right-angled extensions, one of which carries the screw and the other the plunger. Between X and Y, the vertical arms of these extensions, the collimator arm is moved to give the change of wave-length. The micrometer screw passes through a fixed sleeve S graduated in fortieths of an inch. As the screw advances the cylindrical head telescopes on the sleeve S, one of the graduated spaces being traversed with each complete turn of the screw. The forward end of the cylindrical head is bevelled and on the circumference of the bevelled edge is a scale of equal divisions graduated in twenty-fifths of an inch. By means of this scale and the scale on the sleeve S, the advancement of the screw can be read in thousandths of an inch."

(c) "*Collimator Slits.*—One of these slits is of the usual type having carefully beveled knife-edged jaws 12 mm. long, with a micrometer adjustment of width graduated to thousandths of a mm. Such a slit may be used (a) to make a reduction of the spectrum as a whole or of any part, and the reduction may be computed directly from the slit width provided the source is uniformly luminous over the surface exposed; or (b) one part of the spectrum may be made in turn to sustain, within limits and under the conditions mentioned above, any ratio that may be desired to any other part of the spectrum, providing the original intensities from which the reductions are made, are known. This slit, however, is not adapted to just noticeable difference determinations for a given color or range of wave-lengths. The second slit is especially designed for just noticeable difference work. This slit is constructed so that its upper and lower halves are independently variable in width. It was designed especially for the new methods we are using for a quantitative comparative determination of the retina's inertia to the different wave-lengths of light in which just noticeable differences are employed. In the short exposures used in tracing the sensation from the threshold to its maximum, it is obvious that the sectored disc could not be employed in making the variations needed for just noticeable differences. While designed to meet this special need we have found it to be a very convenient means of making the variations needed for much of the general work in just noticeable difference determinations. The slit is formed by three knife-edged jaws. That is, one jaw of the slit is made in one piece

and is 12 mm. long; the other jaw is made in two pieces, each 6 mm. long. One edge, the upper for the upper jaw and the lower for the lower jaw, is beveled to fit into a dovetailed guide cut in the frame. The other edge of each jaw is held in place by a slender close fitting key of appropriate length. The jaw, 12 mm. long, is stationary and the other two jaws are made to move away from it by two independent micrometer screws operated by drum heads graduated to thousandths of a millimeter. In operation the source is adjusted so that one edge of its equally luminous surface is flush with the stationary jaw and the other jaws are pulled away from it exposing as desired different widths of this surface. In a just noticeable difference series one half of the slit is held constant and the other is varied to give the just noticeable difference. When the width of slit needed for this is obtained, that half of the slit is held constant and the other is varied, and so on until the series is completed."

(2) *Apparatus for Presenting the Stimuli to the Eye and for Controlling the time of Exposure.*

(a) *The Lens System.* The apparatus for presenting the stimuli to the eye and controlling the time of exposure consists of the lenses L_3 and L_4, the exposure apparatus and the stimulus-box. The lens L_3, which as stated above focuses the light emerging from the analysing slit S_2 in the plane of the exposure discs, has a focal length of 8.5 centimeters. Two things are required of this lens—(a) it must focus the light accurately on the disc, and (b) the bounding line between the upper and lower halves of the image it forms of the slit S_2 must coincide with the bounding line between the two sets of exposure discs.[38] That is, in order that the time of exposure of the light coming from each half of the double slit shall be independently variable, the open sector of one set of the exposure discs must receive all of the light from one half of the slit; and the open sector of the other set of discs, all of the light from the other half. Both of

[38] This coincidence is, of course, not exact, since the bounding line between the two slits is straight while that between the two sets of discs is circular. In reality the boundary between the two images is tangent to that between the two sets of discs. However, since the width of the image of the slit is only 1 millimeter and the radius of the inner set of discs is 14 centimeters, the deviation of the two boundaries from exact coincidence is negligible for the purposes of these experiments.

these points are conveniently accomplished by having the holder of the lens mounted in an adjustment which gives to it two motions,—one back and forth along the path of the light to adjust the focus, and the other in the vertical to provide for the proper placing of the image on the disc. The lens L_4, which focuses the image of the double slit in the stimulus box, has a focal length of 5 centimeters. It is mounted in a holder the base of which moves in a grooved track parallel to the path of the stimulus light. To provide for accurate focusing, this base is operated by means of a finely threaded screw.

(b) *The Exposure Apparatus.* The exposure apparatus is made up of the rotation apparatus and two specially constructed sectored discs. The rotation apparatus consists of a heavy V-shaped stem with carefully turned bearings, in which rotates a spindle fitted with a special arbor and chuck to hold the exposure disc. Since only a single exposure is wanted for any single observation, the discs are driven by means of a gravity or fall device. That is, attached at its middle to the other end of the spindle, is a rod one meter long which carries on its two arms equal weights. These weights are lead cylinders, which slip on to the rod and are held in position by means of set screws. The rod is graduated in millimeters, so that at any time the position of the weight may be read directly from the scale. Before an exposure the rod is held in position by a catch, the height of which is adjustable. When the catch is released the weight falls rotating the disc D with a velocity depending upon the height of the catch and the position of the two weights on the rod. After the fall, the other end of the rod is caught automatically by another catch. To re-adjust the device for a new observation, the rod is brought back to its original position by hand.

Another factor in determining the length of time of exposure, is the displacement of the open sector from the path of the stimulus light, or its position in the circle of rotation; for, obviously, upon this will depend, with a given height of the catch and a given position of the weights on the driving rod, the amount of acceleration which is given to the disc before the open sector reaches the path of the stimulus light. In making the ex-

posure, the disc was always so adjusted on the axis of rotation apparatus that the light was shut off from the stimulus box when the driving rod was held by the first catch; then, when released one complete exposure had been made before it was caught by the second catch. Since, as stated above, the position of the open sector in the circle of rotation is an important factor in determining the length of exposure which will be obtained with a given value of open sector, height of the catch and position of weights on the driving rod, it is very important to have this position the same at the beginning of each exposure. This was accomplished by drawing a radial line on the disc, when the open sector was in the position desired, so that it just coincided with one edge of the band of stimulus light which was focused on the disc by the lens L_3. A fixed zero is thus established from which the movement of the open sector may be begun at each successive exposure.

(c) *The Stimulus Box.* In careful determination of lag, it is necessary that the stimulus be presented to the eye without the admixture of stray light. In order to accomplish this, the stimulus box B was devised. This apparatus which is very simple in construction is made up of the box proper, a screen to receive the image formed by the lens L_4, and three tubular openings. The box is made of wood and is 52.7 centimeters long, 10.5 centimeters wide, and 11.5 centimeters high. It is painted a mat black, inside and out, and care has been taken to make it light proof except for the three openings mentioned above. One of these openings T_1 is for the admission of the stimulus light; one T_2 for the admission of the light which illuminates the fixation point; and one T_3 for the passage of the stimulus light to the observer's eye. Further to guard against the admission of stray light into the box, these tubes are from two to six inches in length and are painted a mat black on the inside. The screen to receive the image formed by the lens L_4 is at the back of the box in line with the axis of the tube T_3. This screen is of cardboard and is fitted into a holder which can be turned about the vertical axis by a knob. This provision for rotation is made in order that the screen may be brought, in every case that may

arise, into a satisfactory optical relation with the lens L_4 and with the eye. In order to provide a suitable surface on which to view the image formed by the lens L_4, a narrow vertical strip in the center of this screen is covered with magnesium oxide deposited from the burning metal. This surface has a reflection coefficient of 90 per cent and is just large enough to accommodate the image, which is 4 millimeters wide and 15 millimeters high. The remainder of the screen is covered with velvet black paper which has a coefficient of reflection so small as to be negligible in these experiments. In order that the observation shall be begun with the eye accurately adjusted for its stimulus, a fixation point is provided at the exact center of the image formed by the lens L_4. A preliminary adjustment of the eye is especially necessary in work of this kind because of the short interval of time for which the stimuli are exposed. This fixation point is devised in accord with the following requirements. (a) It must be luminous else it can not be seen in the dark field of vision produced by the stimulus box. (b) It should disappear at the instant of the appearance of the stimulus or its light will mix with the stimulus light and modify its action on the eye, and interfere also with the brightness comparison of the two halves of the image. And (c) it should be small and no brighter than is necessary to be seen clearly in order that it may not act to any considerable degree as a pre-exposure and modify, thereby, the sensitivity of the eye to the stimulus light. The last two of these requirements may seem of small consequence; but when methods are used which depend upon the judgment of just noticeable differences, the amounts of sensation involved are as small as possible and the influence of extraneous factors should be reduced to a minimum. This fixation point was obtained by pricking a small hole through the stimulus card at the exact center of the image formed by lens L_4 and illuminating it from behind by a two candle power incandescent lamp, contained in the small lamp-house F. This lamp-house is connected with the stimulus box by the tube T_2 which prevents the light from scattering into the surrounding room; and contains, besides, absorbing screens of the number and diversity needed for reducing the intensity of the light. In

order that the fixation point should disappear simultaneously with the appearance of the stimulus, the following provision is made. The current from the lamp passes from the source to the axis of the rotation apparatus and then to an adjustable collar about this axis, having a sector-like extension. When the rod is held by the catch, this extension makes connection with a flexible brass strip and the current passes through the standard supporting the strip to the lamp and back to the source. The extension is so arranged that, with the rotation of the axis, the connection is broken just as the open sector of the disc allows the light to pass through and form an image on the magnesium oxide surface on the screen at the back of the stimulus box. The breaking of the circuit causes the dot which serves as a fixation point to disappear and prevents its interference with the judgment of the brightness of the lights. A fixation point which shall remain visible until just before the appearance of the stimulus is found to be necessary for accurate work, since otherwise the eye is not in position to receive the stimulus and the shifting of it into position may change the effect of any given exposure.

As has been mentioned before variations in the time of exposure of the stimulus can be introduced in three ways,—(a) by changing the relative position of the weights; (b) by varying the amount of open sector of the disc; and (c) by causing the open sector to cut the beam of light at different points in the revolution of the disc. In order to obtain the exact time of exposure of the stimulus under each of the variations used in the experiments two methods were employed. In the first the procedure was as follows: On the edges of the open sector of the disc were soldered small extensions perpendicular to the disc. These had fine knife edges. Making electrical contact with the knife edges, was the point of a fine coiled spring attached to the end of a horizontal rod. This rod rotated about a vertical standard on a collar, provided with a set screw. By means of the collar and set-screw the rod could be turned until the point of the spring was in the axis of the beam of light which served as the stimulus, and clamped. The spring could then be ex-

tended along the axis of the beam until the point just made contact with the knife-edges as they passed. When the contact was made an electric circuit was completed allowing current to flow from the line through a lamp rheostat, the axis of the rotator, the disc, the knife-edges, spring, rod and its supporting standard to an electric magnetic recorder which marked on the smoked surface of the drum of a kymograph. Directly beneath the record of the electro-magnetic marker a time line was traced by a tuning fork vibrating one hundred times per second. By means of this the interval between the contacts of the spring with the two-knife edges, or the length of exposure of the stimulus light, could be determined. In making these determinations the sectors of the disc were set in each position used in the experiments and a time record made. It was found, after a few trials, that unless extreme care was taken when setting the spring to make the touch on the knife edges as light as possible, a lag was occasioned by the friction of the contact. On account of this possibility of error a second method was used to check up the first. In this method a strip of smoked paper was placed over the open sector of the disc, and the position of the two edges marked carefully on the paper. The pointer of the electric tuning fork was then so adjusted to make a tracing on this strip, care being exercised to make contact as light as possible. From the tracing made by this fork when the disc was rotated, the number of vibrations during the passage of the open sector could be noted directly. In both cases the number of whole vibrations were counted and the measurements of all fractions of vibrations were made on a micrometer comparator, which allowed accurate readings to a thousandth of a millimeter. It was found that the time of exposure, as registered by this method, corresponded with that given by the first method, when care was taken to make the contact as light as possible. We have accepted that value as correct, therefore, and have used it in our tables and curves.

D. *Results*

As was stated in the introductory section of this study, one of the purposes of this investigation was to make a re-determi-

order that the fixation point should disappear simultaneously with the appearance of the stimulus, the following provision is made. The current from the lamp passes from the source to the axis of the rotation apparatus and then to an adjustable collar about this axis, having a sector-like extension. When the rod is held by the catch, this extension makes connection with a flexible brass strip and the current passes through the standard supporting the strip to the lamp and back to the source. The extension is so arranged that, with the rotation of the axis, the connection is broken just as the open sector of the disc allows the light to pass through and form an image on the magnesium oxide surface on the screen at the back of the stimulus box. The breaking of the circuit causes the dot which serves as a fixation point to disappear and prevents its interference with the judgment of the brightness of the lights. A fixation point which shall remain visible until just before the appearance of the stimulus is found to be necessary for accurate work, since otherwise the eye is not in position to receive the stimulus and the shifting of it into position may change the effect of any given exposure.

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tended along the axis of the beam until the point just made contact with the knife-edges as they passed. When the contact was made an electric circuit was completed allowing current to flow from the line through a lamp rheostat, the axis of the rotator, the disc, the knife-edges, spring, rod and its supporting standard to an electric magnetic recorder which marked on the smoked surface of the drum of a kymograph. Directly beneath the record of the electro-magnetic marker a time line was traced by a tuning fork vibrating one hundred times per second. By means of this the interval between the contacts of the spring with the two-knife edges, or the length of exposure of the stimulus light, could be determined. In making these determinations the sectors of the disc were set in each position used in the experiments and a time record made. It was found, after a few trials, that unless extreme care was taken when setting the spring to make the touch on the knife edges as light as possible, a lag was occasioned by the friction of the contact. On account of this possibility of error a second method was used to check up the first. In this method a strip of smoked paper was placed over the open sector of the disc, and the position of the two edges marked carefully on the paper. The pointer of the electric tuning fork was then so adjusted to make a tracing on this strip, care being exercised to make contact as light as possible. From the tracing made by this fork when the disc was rotated, the number of vibrations during the passage of the open sector could be noted directly. In both cases the number of whole vibrations were counted and the measurements of all fractions of vibrations were made on a micrometer comparator, which allowed accurate readings to a thousandth of a millimeter. It was found that the time of exposure, as registered by this method, corresponded with that given by the first method, when care was taken to make the contact as light as possible. We have accepted that value as correct, therefore, and have used it in our tables and curves.

D. *Results*

As was stated in the introductory section of this study, one of the purposes of this investigation was to make a re-determi-

nation of the time required for sensation to reach its maximum by the more promising of the older methods, under conditions which would make possible an inter-comparison of results. After a preliminary trial of the older methods, the ones selected for further investigation were those of Broca and Sulzer, Exner, Dürr and Kunkel. A brief account of the work with Dürr's method was given in our historical section. No further account will be taken of it here. Another feature of the work was, it will be remembered, to devise new methods and to compare the results obtained by these methods with each other, and with those obtained by the older methods. It will be remembered also that one of the purposes in devising new methods was to make it possible directly to compare the different rates of rise of the sensation towards its maximum value for different wave-lengths and intensities of light, as well as to determine the maximum value itself.

The lights selected for investigation were narrow bands taken from the following regions of the prismatic spectrum of a Nernst filament operated at .6 amperes: 686 $\mu\mu$ 580 $\mu\mu$, 511 $\mu\mu$, and 463 $\mu\mu$; and a mixed approximately white light gotten by re-synthesizing this spectrum by means of a cylindrical lens of suitable focal length. The lights at the different intensities used were made photometrically equal. On account of the excessive amount of time and labor required to make the determinations, especially by the older methods, as great a number of intensities of light and regions of the spectrum could not be investigated as was desired. Only three intensities of light were used, for example, and only four parts of the spectrum. The parts of the spectrum selected, however, were those most important for the problem under investigation; as also were the intensities of light, within the limits that could be attained with our apparatus. The photometric values of these intensities were 0.057, 0.151, and 1.21 meter-candles. The energy values of the four monochromatic lights at these three intensities are given in Table VII.[39] The white light was not radiometered.

[39] For the energy meaurements given in this table, the writeer is indebted to Dr. Gertrude Rand.

TABLE VII

		Energy per mm² (watts × 10⁻⁹)	
Wave-lengths	*Photometric value meter-candles*	*At analysing slit*	*At photometer head*
686	1.21	6224.985	65.787
580	"	185.740	1.965
511	"	130.137	1.378
686	0.151	795.422	8.406
580	"	44.337	0.467
511	"	47.657	0.503
463	"	646.040	6.830
686	0.057	238.454	2.522
580	"	2.049	0.221
511	"	1.809	0.191
463	"	189.095	2.001

(1) THE OLDER METHODS

(a) *Broca and Sulzer Method.* In applying the equality of brightness method, heretofore used the most systematically by Broca and Sulzer, the author introduced a modification which, as was stated in the historical part of this study, had not apparently been considered necessary by former investigators, *i.e.* the exposure of the standard light was kept within a very small range of variation. Six seconds was chosen as the best time of exposures to approximate for this light. This choice was determined in part by the following consideration. If the principle of the equality of brightness method, as used by Broca and Sulzer, was to be employed, a longer exposure of the standard light, (2 seconds or more) was demanded than could be obtained with our exposure apparatus. It became necessary, therefore, to adopt a less exact method of regulating and timing the exposure to this light. On this account it was thought better to increase the exposure of the standard light to six seconds, in order that the rate of adaptation of the eye might become sufficiently slow that slight variations in the length of exposure would have little, if any, effect on the apparent brightness of the light.

There are two possible ways of making a series of determinations by this method: either the standard light can be held constant in turn at selected intensities in a graded series and the

length of exposure of the comparison light can be varied until the two appear equal; or, conversely, the intervals of exposure of the comparison light can be graded in value and the intensity of the standard light can be varied to give the judgment of equality. The second of these alternatives was chosen for the work here presented.

The method of making the exposure was as follows: The larger of the two sets of discs of the exposure apparatus was adjusted to give a wide open sector; the smaller, to give an open sector of the value required for the comparison light for the case in question. These sectors were so turned about the axis of the rotator that the edges of sectors that were to terminate the exposures to the two lights were in the same radial line, and the standard light passed through the open sector of the larger disc as closely in front of the forward edge of the open sector of the smaller disc as was possible. This adjustment accomplished three things: (a) The exposure to both lights was terminated simultaneously; (b) prior to the rotation of the disc, the comparison light was shut off from the stimulus box; and (c) only a very small interval of time elapsed between the starting of the rotation apparatus and the ending of the exposure to the comparison light. In the path of the standard light, back of the exposure disc was interposed a shutter. The exposure to the standard light was begun by raising this shutter. It was ended, as indicated above, by the exposure disc. That is, in making a determination, the shutter was raised and, six seconds later, the rotation of the exposure disc was begun, the sectors of which gave the exposure to the comparison light and shut off both lights simultaneously. From this it will be seen that the actual time of exposure to the standard light was in each case six seconds plus the small fraction of a second between the starting of the exposure disc and the ending of the exposure to the comparison light. This increment varied so little from determination to determination, however, that it was considered to have a negligible effect on the apparent brightness of the standard light after six seconds of adaptation. Moreover, for reasons to be stated in the following paragraphs, no attempt will be made

to compare the results obtained by this method with those obtained by other methods for more than one item, namely, the time required for the sensation to reach its maximum. This it will be seen lessens considerably the chance of the above conditions of exposure operating as a significant variable factor.

In the historical discussion, it will be remembered, two serious criticisms were made of this method, as used by Broca and Sulzer. (1) The attempt to rate sensation for comparative purposes in photometric units is fundamentally wrong, for the photometric unit is a unit of light intensity, not of sensation. Two surfaces, for example, illuminated, respectively, by four and one foot-candles of light do not arouse sensations which sustain to each other the ratio of four to one, nor have we any knowledge of what ratio they do sustain to each other. A curve plotted to the just noticeable changes in the intensity of sensation gives, as we have already pointed out, a much better notion of how the sensation rises toward its maximum with different times of action of light on the eye. Since all of our methods are based on the latter type of rating the rise of sensation and since there seems to be no way of passing from one system of values to the other, it is clearly not possible to compare the results obtained by this method and by our own methods on any point but the time required for sensation to reach its maximum. A broader comparison is not allowable for still another reason. This reason is involved in our second point of criticism. (2) Broca and Sulzer did not give the eye the same time of exposure to the standard light either in a given series or from series to series. And even had they made the exposure a constant, as we have done in our use of the method, a fair comparison still could not be made of the values obtained in different parts of the rise; for in determining these values different intensities of standard light have to be used, and the rate of decay of sensation, even for the same length of exposure, is not the same for different intensities of light. This, it is obvious, would vitiate the scale of ratings and make a false showing of comparative values. A comparison does seem permissible, however, so long as the use of only one intensity of standard light is involved in making the

determination, and care is exercised to keep the time of exposure of the eye to this light constant. As has already been seen, these conditions were not satisfied by Broca and Sulzer in any part of their work, and have been satisfied in our work only with regard to one feature of the general problem, namely, the determination of the time required for the sensation to reach its maximum. The values obtained for this time, alone, can be used, therefore, in our inter-comparisons of results.

The results of our work with this method are given in Table VIII and Figure XIII. Since the method has been used only for comparative purposes, the determinations have been made for only one intensity of light. It would be more desirable could several intensities have been used in the work of inter-compari-

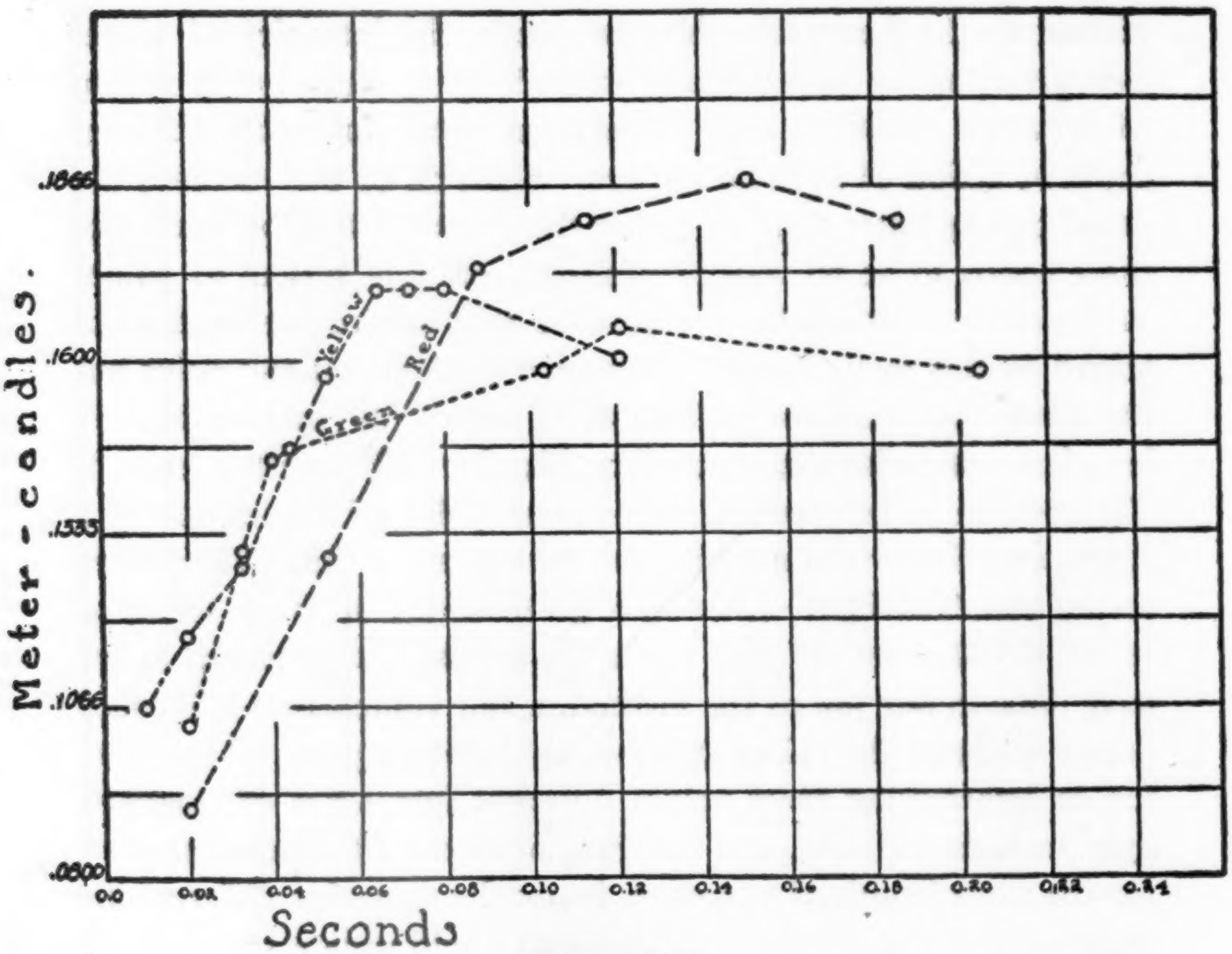

FIGURE XIII

Showing the results of a determination of the rise of sensation by Broca and Sulzer's method as modified by the author. The lights used to produce the sensation under investigation were made photometrically equal at 0.151 meter-candle.

son; but the amount of work involved in making this determination, especially in case of the older methods, was prohibitive of a broader study. For the intensity employed, the time required for the sensation to reach its maximum was for the yellow light 0.065-0.080 seconds; for the green, 0.121 seconds; and for the red, 0.151 seconds. A comparison of these values with those obtained by the other methods for the same intensity of light shows, it will be noted in the tables that follow, a close agreement.

TABLE VIII

Showing the results of a determination of the rise of sensation by Broca and Sulzer's method as modified by the author. The lights used to produce the sensation under consideration (comparison lights) were made photometrically equal at 0.151 meter-candle. In making the determinations the intensity of the comparison light was kept constant and the intervals of exposure were varied; and the intervals of exposure of the standard light was kept constant and its intensity was varied.

Stimulus	*Time of exposure of comparison light in seconds*	*Ratio of intensity of standard and comparison light when judged equal in brightness*	*Intensity of standard light in meter-candles when judged equal in brightness to comparison light*	*Time required for sensation to rise to its maximum value*
Red $686_{\mu\mu}$	0.020	1 : 0.60	0.0900	
	0.053	1 : 0.90	0.1350	
	0.088	1 : 1.17	0.1755	
	0.113	1 : 1.21	0.1815	
	0.151	1 : 1.26	0.1880	0.151
	0.186	1 : 1.21	0.1815	
Yellow $580_{\mu\mu}$	0.100	1 : 0.71	0.1065	
	0.020	1 : 0.78	0.1170	
	0.033	1 : 0.85	0.1275	
	0.053	1 : 1.05	0.1575	
	0.065	1 : 1.14	0.1710	0.065
	0.072	1 : 1.14	0.1710	
	0.080	1 : 1.14	0.1710	
	0.121	1 : 1.07	0.1605	
Green $511_{\mu\mu}$	0.020	1 : 0.68	0.1020	
	0.033	1 : 0.87	0.1305	
	0.040	1 : 0.96	0.1440	
	0.044	1 : 0.98	0.1470	
	0.121	1 : 1.10	0.1650	0.121
	0.130	1 : 1.06	0.1590	
	0.205	1 : 1.06	0.1590	

(b) *Exner's Method.* In case of this method the author has adopted the procedure originated and used by Exner in 1870 with one modification,—the judgment of the relative brightness of the two lights was made of the original stimuli at the moment of their disappearance. That is a comparison of the positive after-images was not made, as Exner states was done by him.[40] In this method, it will be remembered, the two stimuli are of equal intensity; but the exposure of one is started before the exposure of the other. From a consideration of these conditions, it is obvious that the sensations aroused by the two lights can not be judged equal at the exact maximum for either. The sensation aroused by the shorter exposure will not have reached its maximum; while the sensation aroused by the longer exposure will have passed beyond its maximum. That is, the judgment of equality will be made when the loss in brightness due to the decay of the one is equal to the deficiency due to the under-development of the other. Now by variations, from small to great, in the differences in the lengths of exposures of the two lights, a series of values can be found which lie by increasingly greater amounts on either side of the maximum. The following cases are possible. (a) If the difference is very small the two stimuli will be judged equal for all, or nearly all, of the lengths of time for which they can be exposed. (b) If the difference is made larger, the stimuli will be judged equal for a range of exposures including the maximum and a range on either side of the maximum, the size of the range depending on the magnitude of the difference of the two exposures. And (c) if the difference is made still larger the stimuli will be judged equal for each value of the difference at only one length of exposure for either of the two stimuli. In this case the sensation aroused by the light first exposed will have passed its maximum value and the sensation aroused by the light last exposed will not have reached its maximum value. The maximum would be approximately the mean of these two values provided the rate of decay of sensation is equal,

[40] The author, like others who have tried this method, was unable to make any judgment in terms of the after-response, in fact, no definite positive or negative after-images could be detected.

or nearly so, for the intervals in question, to the rate of development. This for short intervals just before and just after the maximum is reached, does not seem to be far from true. One way of estimating the time required to obtain the maximum, then would be to take the mean of these exposures arousing equal values in sensation whose differences are small enough, on the one hand, to fall within the region of equal rates of rise and decay about the maximum and large enough, on the other hand, that the judgment of equality can be given for only one or, at most only a very small range of exposures. Another way would be to assume with Exner that when the difference of the time of exposure of the two lights is as small as is possible, under the conditions necessary to the experiment the interval for which the judgment of equality is made is, for the first exposed, the time required for it to arouse its maximum response. But taken literally this assumption is not correct, for as we have already pointed out, the difference in the time of exposure to the two lights may be made so small that the two sensations would be judged equal for all or the greater number of values of exposure that might be used; and (b) the time of exposure for neither light can be the optimum time of exposure for that light. Both on account of its indefiniteness and relatively greater inaccuracy, no attempt has been made to apply Exner's method for estimating any point but the maximum.

Our procedure in carrying out this method was as follows: A given difference in the values of the open sectors of the double exposure disc for the two stimuli, was chosen. The lengths of exposure of the two stimuli were then varied until values were obtained for which the light, whose exposure was begun first, was judged in turn lighter, equal, and darker than the other light. Another constant difference of open sector[41] was then chosen and the series was repeated.

[41] On account of the difference in the inertia of the discs of the exposure apparatus when set with different total open sectors equal difference in open sector did not mean equal difference in exposure time. The author found it necessary to measure the time for each setting separately. This procedure allowed the experimenter to find points on opposite sides of the maximum which were judged equal, and therefore to reckon the maximum.

The results of this method are given in Table IX. They are not given, however, in the order in which they were obtained; but have been arranged for the convenience of the reader into groups in which the light longer exposed was judged, respectively, lighter, equal, and darker than the light exposed for the shorter time. Our method of estimating the optimum length of exposure can, perhaps, be made clearer by an example from the table. For this purpose the results for only one color need be considered, namely, red. The table shows that, in case of this color, the sensations aroused by nine pairs of exposures were judged equal. In accord with our criteria stated above, three pairs of these were discarded—0.070 and 0.101 seconds, 0.170 and 0.192 seconds, and 0.140 and 0.170 seconds—because the difference in time of exposure between the members of the pairs in each case was too small, as shown by the other data in this table, to produce a just noticeable difference in sensation. That is, it is seen that in another place in the table the exposures, 0.140 and 0.070 seconds, for example, gave a judgment of lighter in favor of the longer exposure. This shows that 0.101 is less than the optimum value of exposure for red and that the judgment of equality was given in the first and third of the above cases, not because the optimum exposure was attained, but because the difference between the two exposures,—0.03 seconds in each case,—was too small to cause a just noticeable difference in sensation. Since all the work has shown that in general, within the range of exposures used, a greater difference in length of exposure is required to give a just noticeable difference in sensation as the order of magnitude of both exposures is increased, it can hardly be assumed that the difference in the length of the two exposures in the second case, 0.022 seconds, was sufficient to cause a just noticeable difference in sensation. It does not seem fair, therefore, to use this result, in the estimation of the average either, although so clear a reason for discarding it is not present as was the case for the other pairs of exposures. That is, a judgment of equality can not be considered as evidence that the critical values needed for the estimation of the optimum exposure have been attained when the judgment might

TABLE IX

Showing the results of a determination of the rise of sensation by Exner's methods modified by the author. The lights used to produce the sensation under investigation were made photometrically equal at 0.057 meter-candles. The light the exposure of which was begun first, is referred to in the table as the standard light, the other is referred to as the comparison light.

Stimulus	Time of exposure in seconds: Standard light.	Time of exposure in seconds: Comparison light.	Difference in time of exposure of the two lights.	Judgment of brightness of standard light in terms of comparison light.	Mean values of exposures needed to make the two lights appear equally bright.	Time required for sensation to reach its maximum.
Red 686$\mu\mu$	0.072	0.050	0.022	lighter		
	0.140	0.070	0.070	"		
	0.178	0.128	0.050	"		
	0.182	0.132	0.050	"		
	0.188	0.136	0.052	"		
	0.192	0.096	0.096	"		
	0.101	0.070	0.031	equal	(omitted)*	
	0.170	0.140	0.030	"	"	
	0.192	0.170	0.022	"	"	
	0.192	0.156	0.036	"	0.174	
	0.182	0.140	0.042	"	0.161	
	0.192	0.120	0.072	"	0.156	0.161
	0.198	0.132	0.066	"	0.165	
	0.198	0.111	0.087	"	0.154	
	0.203	0.120	0.083	"	0.161	
	0.203	0.140	0.063	darker		
	0.207	0.125	0.082	"		
	0.203	0.170	0.033	"		
	0.211	0.178	0.033	"		
Yellow 580$\mu\mu$	0.101	0.044	0.057	lighter		
	0.120	0.070	0.050	"		
	0.124	0.075	0.049	"		
	0.101	0.075	0.026	"		
	0.124	0.101	0.023	"		
	0.064	0.038	0.026	"		
	0.128	0.080	0.048	equal	0.104	
	0.134	0.085	0.049	"	0.109	
	0.106	0.080	0.026	"	0.093	
	0.110	0.085	0.025	"	0.097	0.099
	0.136	0.090	0.046	"	0.113	
	0.120	0.096	0.024	"	0.108	
	0.115	0.075	0.040	"	0.095	

TABLE IX (continued)

Stimulus	Time of exposure in seconds: Standard light.	Time of exposure in seconds: Comparison light.	Difference in time of exposure of the two lights.	Judgment of brightness of standard light in terms of comparison light.	Mean values of exposures needed to make the two lights appear equally bright.	Time required for sensation to reach its maximum.
	0.085	0.070	0.015	equal	(omitted)*	
	0.115	0.101	0.014	"	"	
	0.140	0.096	0.044	darker		
	0.146	0.101	0.045	"		
Green 511$\mu\mu$	0.170	0.120	0.050	lighter		
	0.182	0.188	0.024	"		
	0.192	0.120	0.072	"		
	0.203	0.140	0.063	"		
	0.215	0.158	0.057	"		
	0.224	0.140	0.084	"		
	0.250	0.140	0.110	"		
	0.203	0.170	0.033	equal	0.186	
	0.224	0.170	0.054	"	0.197	
	0.236	0.170	0.066	"	0.203	0.193
	0.261	0.150	0.091	"	0.205	
	0.192	0.160	0.032	"	0.176	
	0.271	0.192	0.079	darker		
Blue 463$\mu\mu$	0.170	0.120	0.050	lighter		
	0.203	0.170	0.033	"		
	0.215	0.158	0.057	"		
	0.224	0.140	0.084	"		
	0.231	0.152	0.079	"		
	0.235	0.165	0.070	"		
	0.211	0.178	0.034	equal	0.194	
	0.224	0.192	0.032	"	0.208	
	0.250	0.224	0.026	"	0.237	
	0.236	0.203	0.033	"	0.218	
	0.228	0.196	0.032	"	0.212	0.210
	0.224	0.170	0.054	"	0.197	
	0.236	0.192	0.044	"	0.214	
	0.236	0.170	0.066	"	0.203	
	0.240	0.178	0.068	"	0.209	
	0.254	0.228	0.026	darker		
	0.250	0.203	0.047	"		
	0.240	0.196	0.044	"		
	0.248	0.188	0.060	"		

* These numbers were omitted from the final calculation of the time required for the sensation to reach its maximum value for reasons stated in the text. (See p. 72.)

just as well have been due to the insufficient difference in the length of the two exposures to give any but a judgment of equality. The optimum time of exposure, was estimated, therefore, from the six remaining pairs of exposures that gave the judgment of equality. So estimated, the optimum for red of the intensity and range of wave-lengths used was found to be 0.161 seconds. By a similar method of estimation the optimum for yellow, green, and blue were, respectively 0.099 seconds, 0.193 seconds, 0.210 seconds. These values, it will be observed, agree very well with the results obtained by the other methods of determining the maximum.

(c) *Kunkel's Method.* In applying this method, it will be remembered that two conditions are essential. (1) The lights used must be of different intensities. One, the standard light, must be a great deal stronger than the other, the comparison light, and, if the method is to accomplish its purpose, the sensation aroused by the stronger light must, as assumed by Exner, rise more rapidly towards its maximum than that aroused by the weaker light. The intervals of exposure of the two lights must be so regulated, however, that the sensation aroused by the weaker light reaches its maximum before that aroused by the stronger light. And (2) a variable and not a constant difference in the time of exposure of the two lights must be employed in each series of determinations. That is, the apparatus is so arranged that the exposure to the two lights end at the same time. A given very small interval of exposure is chosen for the comparison light. Then a time of exposure is found for the standard light which causes it just to match the comparison light in apparent brightness. This procedure is repeated for a graded series of exposures for the comparison light. From this series that value of exposure of the comparison light is selected as optimum, which is matched in its effect on sensation by the longest in the series of exposures given to the standard light. (See more detailed description of method, p. 26.) In our use of this method a standard light was chosen, approximately twice as intense as the comparison light.[42] A short initial exposure

[42] In striving for precision by this method, two factors must be taken into

then was given to the standard light and the exposure of the comparison light was varied until at the moment of disappearance it was judged lighter than the standard light. The length of exposure of the standard was then increased until it was judged equal in brightness to the comparison. This procedure was continued until an exposure was found for the standard light which aroused a sensation which could be matched, but never exceeded, by the sensation aroused by the comparison light, however, much its exposure was increased. In accord with the principal of the method, this exposure was chosen as the optimum for the comparison light.

Table X shows a typical set of results for this method. They are published complete with the exception that exposures of the standard light which were too short to give any judgments of equality are omitted. In the first column is given the stimuli with the region of the spectrum from which it was taken; in the second and third, the intervals of exposure of the standard and comparison lights, respectively; and in the fourth column, the judgment of the comparison light in terms of the standard. A great help in understanding the application of this method can be had by comparing columns 2, 3 and 4.

The results show that, although the intervals required for the colors to rise to their maximum are in the same order as for the other methods, the actual values of the exposures are in each case slightly greater. This is true consistently for all of the colors. A reason for this may be found, perhaps, in the discussion of methods given earlier in the paper. (See discussion of Dürr's method, p. 30.) That is, when a standard light very much

account. (1) The more intense is the standard light, the more rapid is the rise of the sensation which it arouses. With the greater intensities of standard light there is, therefore, a greater variation of apparent brightness per unit of time. If there were no counteracting influences this should lead to a greater precision in isolating the optimum exposure for the comparison light. That is, a smaller range of exposures could give a sensation which matches the sensation aroused by any one exposure of the standard light. But (2) if too intense a light is chosen for the standard, its time of exposure must be made very short to be available in the series, and the judgment is thereby rendered more difficult. For the author the best results were obtained with a standard light of about twice the intensity of the comparison light.

TABLE X

Showing the results of a determination of the rise of sensation by Kunkel's method. The lights used to produce the sensations under investigation were made photometrically equal at 0.057 meter-candles.

Stimulus	*Time of exposure of standard light in seconds*	*Time of exposure of comparison light in seconds*	*Judgment of brightness of comparison light in terms of standard light*	*Time required for sensation to reach its maximum value*
Red 686$\mu\mu$	0.038	0.120	lighter	
	0.054	0.120	equal	
	0.054	0.170	lighter	
	0.070	0.164	darker	
	0.070	0.170	equal	
	0.070	0.203	"	0.196
	0.070	0.217	"	
	0.070	0.224	darker	
	0.070	0.250	"	
Yellow 580$\mu\mu$	0.026	0.070	lighter	
	0.032	0.070	equal	
	0.032	0.096	lighter	
	0.038	0.096	lighter	
	0.042	0.096	lighter	
	0.044	0.096	equal	
	0.044	0.120	equal	
	0.044	0.115	lighter	
	0.047	0.120	darker	
	0.047	0.115	equal	0.115
	0.047	0.096	darker	
Green 511$\mu\mu$	0.070	0.170	lighter	
	0.080	0.170	equal	
	0.080	0.203	lighter	
	0.090	0.203	lighter	
	0.096	0.224	darker	
	0.096	0.216	equal	0.207
	0.096	0.198	equal	
	0.096	0.196	darker	

stronger than the comparison is used, the result is apparently to lengthen the time necessary for the sensation to reach its maximum; but this lengthening is less where the post-exposure is white instead of black—a fact which seems to show that the positive after-image has an effect on the determination of the

kind described above. Here, however, this effect does not seem so pronounced as it was with the method used by Dürr. Two reasons may, probably, be assigned for this: (a) the ratio of intensity of the standard and comparison lights is not so large; and (2) the time of exposure of the standard light is much shorter. Both of these factors, according to the results of Franz (given earlier in this paper, p. 33) would tend to lessen the effect of the positive after-image; still it is very conceivable that the positive after-image may have an effect when the judgment has to be made just at the moment both stimuli disappear, as is the case in work of this kind. In any event the lack of agreement falls within a just noticeable difference, an amount which can hardly be considered of great significance since the effect on sensation of a smaller difference in exposure could not be detected. In fact, the author has sought an explanation of the disagreement only because it was consistently in the same direction.

(2) THE NEWER METHODS

(a) *Method 1.* The first step in this method, it will be remembered, is to establish a just noticeable difference series for each color to serve as a series of graded standard sensations against which to match the sensation under investigation at the various stages in its rise to the maximum. In determining this series of just noticeable differences, the time of exposure to the standard light was kept constant at 0.261 seconds and the changes in sensation were produced by varying the widths of the two halves of the collimator slit. In doing this the two halves served in alternation as standard and comparison until a series of sufficient length was obtained, *i.e.* the lower half, for example, was held constant and the upper half was varied until a just noticeable difference in sensation was produced; and then the upper half was held constant at the last setting of the previous determination and the lower half was varied, etc. until the end of the series was reached. The sensation under investigation was then compared with the different members of the series, the object being to find a time of exposure to the comparison light that

would arouse a sensation which would match in turn each just noticeably different step in the series until the maximum was reached. For example, a yellow stimulus of 0.151 meter candles, when its time of exposure was 0.051 seconds gave a sensation which was judged equal to the fifth just noticeable difference in the series. When a point is reached beyond which no higher step in the series can be matched by making any further increase in the time of exposure to the comparison light, it is concluded that the maximum response to that light has been attained. Two intensities of light were used with this method for each range of wave-length, —0.057 meter candles and 0.151 meter candles. The results of the determinations are given in Tables XI, and XII, and figures XIV and XV. It will be noted in these tables that time has not been taken to match each just noticeable difference in the standard series.

Table XI

Showing the results of a determination of the rise of sensation by Method 1. The lights used to produce the sensation were made photometrically equal at 0.057 meter-candles.

Stimulus	*Time of exposure of comparison light in seconds*	*Just noticeable difference in standard series to which the sensation aroused by the comparison light is judged equal*	*Time required for sensation to rise to its maximum value*
Red 686$\mu\mu$	0.015	1	
	0.035	3	
	0.060	4	
	0.117	6	
	0.160	7	0.160
	0.185	6	
Yellow 580$\mu\mu$	0.020	2	
	0.060	5	
	0.085	6	
	0.105	7	0.105
	0.162	5	
Green 511$\mu\mu$	0.020	1	
	0.035	2	
	0.060	4	
	0.105	5	
	0.183	7	0.183
	0.262	6	

TABLE XII

Showing the results of a determination of the rise of sensation by Method 1. The lights used to produce the sensation were made photometrically equal at 0.151 meter-candles.

Stimulus	*Time of exposure of comparison light in seconds*	*Just noticeable difference in standard series to which the sensation aroused by the comparison light is judged equal*	*Time required for sensation to rise to its maximum value*
Red $686\mu\mu$	0.030	2	
	0.051	4	
	0.085	6	
	0.105	7	
	0.144	8	0.144
	0.262	7	
Yellow $580\mu\mu$	0.020	2	
	0.029	4	
	0.035	5	
	0.060	6	
	0.095	8	0.095
	0.183	7	
Green $511\mu\mu$	0.020	1	
	0.030	3	
	0.065	6	
	0.105	8	
	0.144	9	0.144
	0.262	8	

(b) *Method 2.* Method 2 is an indirect method and has not the same *a priori* claim to sureness of principle as has Methods 1 and 3. The method is based on the assumption that the time of exposure that gives the greatest number of just noticeable changes from the zero of sensation, is the time most favorable for light of that intensity to produce sensation, in other words is the time which just allows the sensation to reach its maximum. Besides determining for us the time of exposure which gives the maximum value of the sensation, the method also provides a means of rating the sensation values for different times of exposure in terms of just noticeable differences from the zero. The application of the method is as follows: Beginning with a very short time of exposure a just noticeable difference series is de-

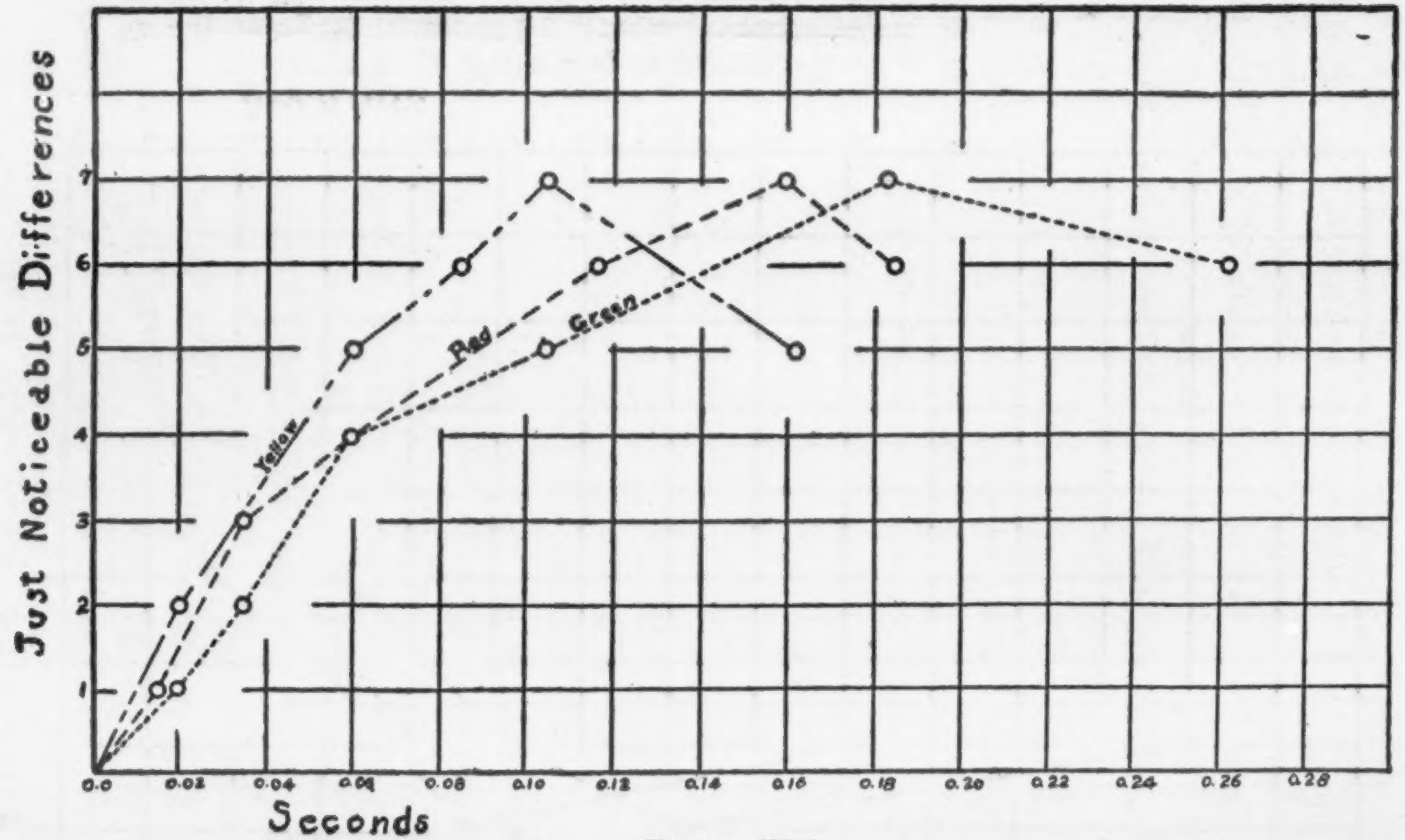

FIGURE XIV

Showing the results of a determination of the rise of sensation by Method 1. The lights used to produce the sensations under investigation were made photometrically equal at 0.057 meter-candles.

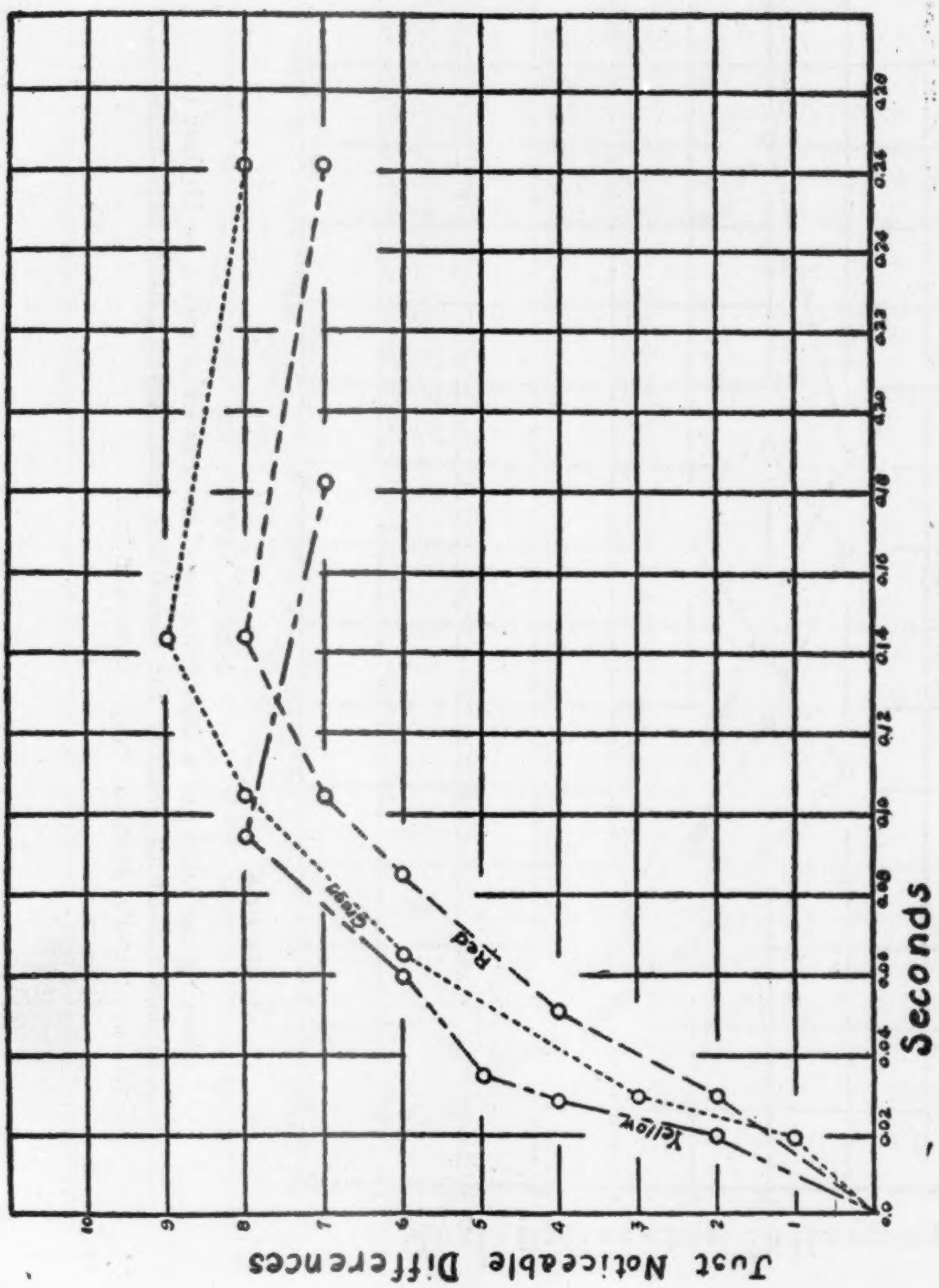

FIGURE XV

Showing the results of a determination of the rise of sensation by Method I. The lights used to produce the sensations under investigation were made photometrically equal at 0.151 meter-candles.

termined. This determination is repeated with a slightly longer time of exposure. The determinations are continued, with small increases in the time of exposure, until one is found that gives the greatest number of just noticeable differences from the zero of sensation for the light in question. This time of exposure is selected as the optimum, and the comparative values of the other exposures for producing sensation are rated by the number of just noticeable differences that were produced by each. The small changes of intensity, needed for making the just noticeable difference determinations, were obtained by means of the double collimator slit, previously described. The procedure in making the determinations was the same as used in Method 1. The results obtained by the method are shown in Table XIII and figure XVI. Since an entire just noticeable difference series has to be determined for each interval of exposure, the time and labor involved in using the method is great. For this reason it has been employed in this investigation only as far as was needed to afford a comparison with the results of other methods. A comparison of results with those of Methods 1 and 3 shows the following points of similarity: the number of just noticeable differences between the zero and the maximum is the same; the order of rate of rise for the different colors, also, is the same; and the agreement in the lengths of exposure that are required to give the maximum of sensation, is fairly close.

Attention may be called in passing to a difficulty in applying the method which is, perhaps, responsible for the lack of smoothness of the curves. Obviously the setting for a just noticeable difference does not, for every value of exposure that may be selected, coincide with the slit width representing the intensity of light used. Since the just noticeable difference can not be fractioned, the next lower integral value was taken in each case for the number of just noticeable differences produced by the given time of exposure. The cases in which the difficulty occurred, necessitated the correlation of the given number of just noticeable differences with a time of exposure a little longer than the correct value. With time and patience it would, of course, have been possible to have determined with minute exactness the in-

terval needed just to give the number of just noticeable differences in question. This should have resulted in smoother curves. The results. moreover, would have been more strictly comparable with those obtained by other methods.

TABLE XIII

Showing the results of a determination of the rise of sensation by Method 2. The light used to produce the sensations under investigation were made photometrically equal at 0.057 meter-candles.

Stimulus	*Time of exposure of lights in seconds*	*Number of just noticeable differences in sensation produced by increasing the stimulus from 0 to 0.057 meter-candles*	*Time required for sensation to rise to its maximum value*
Red 686$\mu\mu$	0.015	1	
	0.065	4	
	0.137	6+*	
	0.161	7+	0.161
	0.260	6	
Yellow 580$\mu\mu$	0.010	1	
	0.065	5	
	0.103	7	0.103
	0.161	5	
Green 511$\mu\mu$	0.020	1	
	0.065	3+	
	0.121	5	
	0.161	6	
	0.186	7+	0.186
	0.262	6+	
Blue 463$\mu\mu$	0.015	1	
	0.065	3+	
	0.121	4+	
	0.140	5	
	0.205	7	0.205
	0.262	6	

(c) *Method 3.* In this as in the former methods, it will be remembered, the sensation in its rise towards the maximum is graded in terms of just noticeable differences; but that just noticeable differences are produced by changes in the time of exposure, the intensity of the light being kept constant throughout.

* The sign indicates that the given just noticeable difference ended before 0.057 meter-candles was reached, but that the next just noticeable difference carried it beyond this intensity.

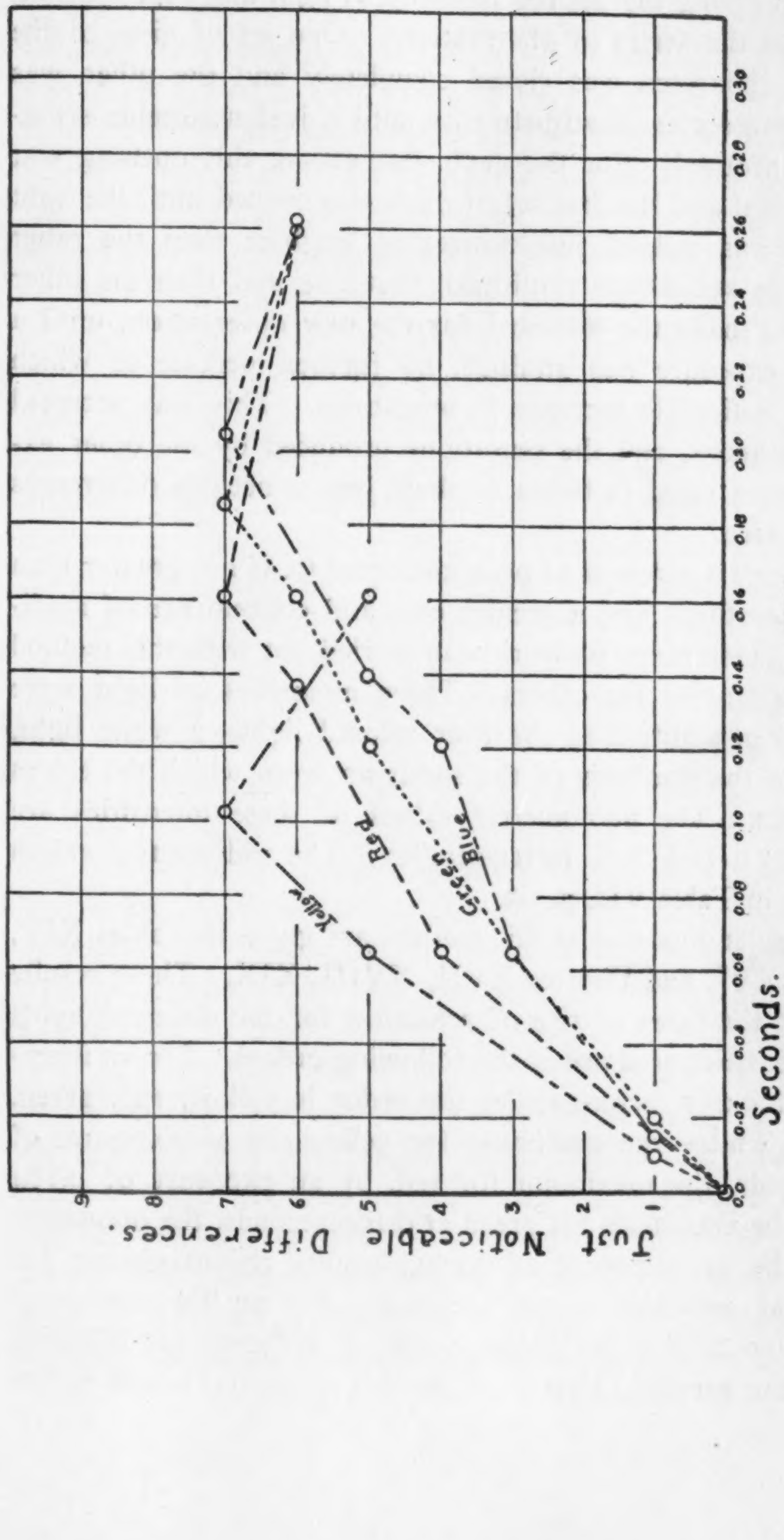

FIGURE XVI

Showing the results of a determination of the rise of sensation by Method 2. The lights used to produce the sensations under investigation were made photometrically equal at 0.057 meter-candles.

The procedure in applying the method is as follows: The upper and lower halves of the double slit of the collimator were set at a width giving the desired intensity of light and kept constant throughout the series of observations. One set of discs of the exposure apparatus was closed completely and the other was opened by a series of adjustments until a just noticeable sensation was aroused. For the next observation, this opening was held constant and the first set of discs was opened until the light admitted was judged just noticeably brighter than the other light. The series was continued, first one and then the other light being made the standard for the new observation, until a value of exposure was attained, no further increase of which caused a noticeable increase in brightness. This was accepted as the optimum, and the sensations produced by the other exposures were rated in terms of their just noticeable differences from the zero.

Because of a sureness of principle equal to, if not greater than any of the others, and a greater ease and convenience of application, a wider range of work was carried out with this method than with any of the others. Three intensities of light were used; and in addition to the four colored lights, a white light, formed by the synthesis of the spectrum from which the colors were taken. The photometric values of these intensities are 0.057, 0.151, and 1.21 meter-candles. The radiometric values are given in Table VII, p. 65.

The results obtained by this method are given in Tables XIV, XV, and XVI, and Figures XVII, XVIII, XIX. These results show that the rates of rise of sensation for the different lights at the intensities used are in the following orders. For an illumination of 0.057 meter-candles the order is yellow, red, green, blue, and white—the maximum for yellow, by an exposure of 0.10 seconds, the maximum for red, by an exposure of 0.164 seconds, the maximum for green at 0.190 seconds, the maximum for blue by an exposure of 0.210 seconds, the maximum for white by an exposure of 0.216 seconds. For an illumination of 0.151 meter-candles the order of rise is different for different parts of the curves. That is, in passing from the lowest to the

highest of the three intensities, there is a marked difference in the order of rise of the colors amounting to a reversal for the pairs of colors red and yellow, and blue and green. In case of the intermediate intensity, as might perhaps be expected, the tendency in the low part of the curves seems to be roughly following the order of rise that was shown in the curves for the lower intensity; and in the upper part of the curves, to follow the tendency shown in the curves for the higher intensity.

In case of this intermediate intensity, the maximum for yellow was produced by an exposure of 0.086 seconds; for blue, by an exposure of 0.134 seconds; for green, by an exposure of 0.146 seconds; for red, by an exposure of 0.148 seconds, and for white, by an exposure of 0.184 seconds. For the highest intensity 1.211 meter-candles, blue could not be obtained with the apparatus used. The order of rise for the remaining lights, up to within two just noticeable differences of the maximum for green, is green, yellow, white and red. At this point green lags behind the other colors. The maximum for yellow, we find, is produced by an exposure 0.088 seconds; for red, by an exposure of 0.100 seconds; for white, by an exposure of 0.105 seconds; and for green, by an exposure of 0.136 seconds. It will be noted in a consideration of these tables and curves that the lights judged photometrically equal by the equality of brightness method have the same number of just noticeable differences between the zero and the maximum, with the exception of green for the intermediate and highest intensity and white for the intermediate intensity. The additional just noticeable difference, found with these two lights in the cases mentioned, may be an individual peculiarity. In this connection it should be remembered, however, as we have stated in our introductory chapter, that owing to the different rates of rise and decay of sensation for lights of different composition, a photometric balance established for different wave-lengths can be considered as valid only for the particular lengths of exposure of the eye used in making the balance. That is, if a longer or shorter exposure should be used, there is no *a priori* reason to expect that the balance would be valid. Since the photometric balance for the above lights was

made with a length of exposure different from the time required for each to give its maximum effect on sensation it is not strange from *a priori* considerations that a rating of these lights made with an exposure of the time required for each to give its maximum effect should be found to differ in one or more cases from the photometric rating. The shift in the order of rise for the colors with increase of intensity which these results show, may account for some of the variations in the results which have been obtained by different observers. In the work of previous investigators, it will be remembered, no care was taken to duplicate the intensities of light used by other investigators.

TABLE XIV

Showing the results of a determination of the rise of sensation by Method 3. The lights used to produce the sensation under investigation were made photometrically equal at 0.057 meter-candles.

Stimulus	*Time of exposure in seconds* *Standard light*	*Comparison light*	*Judgment of brightness of comparison light in terms of standard light*	*Time required for sensation to rise to to its maximum value*
Red 686$\mu\mu$	0.000	0.010	lighter	
	0.010	0.026	"	
	0.026	0.044	"	
	0.044	0.062	"	
	0.062	0.095	"	
	0.095	0.123	"	
	0.123	0.164	"	0.164
	0.164	0.210	darker	
Yellow 580$\mu\mu$	0.000	0.005	lighter	
	0.005	0.015	"	
	0.015	0.026	"	
	0.026	0.042	"	
	0.042	0.056	"	
	0.056	0.080	"	
	0.080	0.103	"	0.103
	0.103	0.121	darker	
	0.121	0.137	"	
	0.137	0.164	"	
Green 511$\mu\mu$	0.000	0.020	lighter	
	0.020	0.033	"	
	0.033	0.046	"	
	0.046	0.072	"	
	0.072	0.113	"	

TABLE XIV (Continued

Stimulus	Time of exposure in seconds Standard light	Comparison light	Judgment of brightness of comparison light in terms of standard light	Time required for sensation to rise to to its maximum value
	0.113	0.151	lighter	
	0.151	0.190	"	0.190
	0.190	0.245	darker	
Blue 463$\mu\mu$	0.000	0.010	lighter	
	0.010	0.026	"	
	0.026	0.044	"	
	0.044	0.072	"	
	0.072	0.113	"	
	0.113	0.156	"	
	0.156	0.210	"	0.210
	0.210	0.261	darker	
White	0.000	0.046	lighter	
	0.046	0.057	"	
	0.057	0.078	"	
	0.078	0.105	"	
	0.105	0.138	"	
	0.138	0.179	"	
	0.179	0.216	"	0.216
	0.216	0.271	darker	
	0.271	0.327	"	

TABLE XV

Showing the results of a determination of the rise of sensation by Method 3. The lights used to produce the sensation under investigation were made photometrically equal at 0.150 meter-candles.

Stimulus	Time of exposure in seconds Standard light	Comparison light	Judgment of brightness of comparison light in terms of standard light	Time required for sensation to rise to its maximum value in seconds
Red 686$\mu\mu$	0.000	0.007	lighter	
	0.007	0.015	"	
	0.015	0.033	"	
	0.033	0.049	"	
	0.049	0.077	"	
	0.077	0.106	"	
	0.106	0.134	"	
	0.134	0.148	"	0.148
	0.148	0.184	darker	
	0.184	0.212	"	
	0.212	0.255	"	

TABLE XV (Continued)

Stimulus	*Time of exposure in seconds* — *Standard light*	*Comparison light*	*Judgment of brightness of comparison light in terms of standard light*	*Time required for sensation to rise to its maximum value in seconds*
Yellow 580$\mu\mu$	0.000	0.007	lighter	
	0.007	0.015	"	
	0.015	0.024	"	
	0.024	0.033	"	
	0.033	0.044	"	
	0.044	0.056	"	
	0.056	0.068	"	
	0.068	0.086	"	0.086
	0.086	0.113	darker	
	0.113	0.137	"	
Green 511$\mu\mu$	0.000	0.010	lighter	
	0.010	0.020	"	
	0.020	0.031	"	
	0.031	0.042	"	
	0.042	0.051	"	
	0.051	0.068	"	
	0.068	0.086	"	
	0.086	0.113	"	
	0.113	0.146	"	0.146
	0.146	0.206	darker	
	0.206	0.246	"	
Blue 463$\mu\mu$	0.000	0.010	lighter	
	0.010	0.015	"	
	0.015	0.020	"	
	0.020	0.036	"	
	0.036	0.053	"	
	0.053	0.080	"	
	0.080	0.109	"	
	0.109	0.134	"	0.134
	0.134	0.148	darker	
	0.148	0.174	"	
	0.174	0.245	"	
White	0.000	0.034	lighter	
	0.034	0.046	"	
	0.046	0.055	"	
	0.055	0.066	"	
	0.066	0.080	"	
	0.080	0.098	"	
	0.098	0.124	"	
	0.124	0.151	"	
	0.151	0.184	"	0.184
	0.184	0.206	darker	

TABLE XVI

Showing the results of a determination of the rise of sensation by Method 3. The lights used to produce the sensation under investigation were made photometrically equal at 1.21 meter-candles.

Stimulus	*Time of exposure in seconds* — *Standard light*	*Comparison light*	*Judgment of of brightness of comparison light in terms of standard light*	*Time required for sensation to rise to its maximum value in seconds*
Red 686$\mu\mu$	0.000	0.003	lighter	
	0.003	0.007	"	
	0.007	0.012	"	
	0.012	0.016	"	
	0.016	0.021	"	
	0.021	0.026	"	
	0.026	0.033	"	
	0.033	0.044	"	
	0.044	0.052	"	
	0.052	0.063	"	
	0.063	0.078	"	
	0.078	0.090	"	
	0.090	0.100	"	0.100
	0.100	0.129	darker	
	0.129	0.153	"	
Yellow 580$\mu\mu$	0.000	0.002	lighter	
	0.002	0.004	"	
	0.004	0.007	"	
	0.007	0.010	"	
	0.010	0.015	"	
	0.015	0.020	"	
	0.020	0.026	"	
	0.026	0.033	"	
	0.033	0.043	"	
	0.043	0.055	"	
	0.055	0.069	"	
	0.069	0.086	"	
	0.086	0.088	"	0.088
	0.088	0.106	darker	
	0.106	0.126	"	
Green 511$\mu\mu$	0.000	0.002	lighter	
	0.002	0.004	"	
	0.004	0.006	"	
	0.006	0.009	"	
	0.009	0.011	"	
	0.011	0.013	"	
	0.013	0.016	"	

TABLE XVI (Continued)

Stimulus	Time of exposure in seconds: Standard light	Comparison light	Judgment of of brightness of comparison light in terms of standard light	Time required for sensation to rise to its maximum value in seconds
	0.016	0.022	lighter	
	0.022	0.034	"	
	0.034	0.046	"	
	0.046	0.060	"	
	0.060	0.072	"	
	0.072	0.112	"	
	0.112	0.136	"	0.136
	0.136	0.160	darker	
White	0.000	0.004	lighter	
	0.004	0.007	"	
	0.007	0.008	"	
	0.008	0.013	"	
	0.013	0.018	"	
	0.018	0.022	"	
	0.022	0.028	"	
	0.028	0.036	"	
	0.036	0.044	"	
	0.044	0.057	"	
	0.057	0.072	"	
	0.072	0.088	"	
	0.088	0.105	"	0.105
	0.105	0.122	darker	

As stated in a preceding section, one of the objects of the work has been an intercomparison of the results obtained, both by the new methods and such of the older ones as seemed possible, from the same observer working under the same experimental conditions and with the same wave-lengths and intensities of light. In order to facilitate such a comparison, the results for each color by all of the methods have been represented in the same chart. For the three new methods, curves have been plotted showing the rates of rise of sensation to the maximum in terms of just noticeable difference steps. This could not be done, of course, for the methods of Broca and Sulzer, Exner, and Kunkel, since these methods provide a means of determining only the time required for the sensation to rise to its maximum. All that could be done in those cases was to represent the

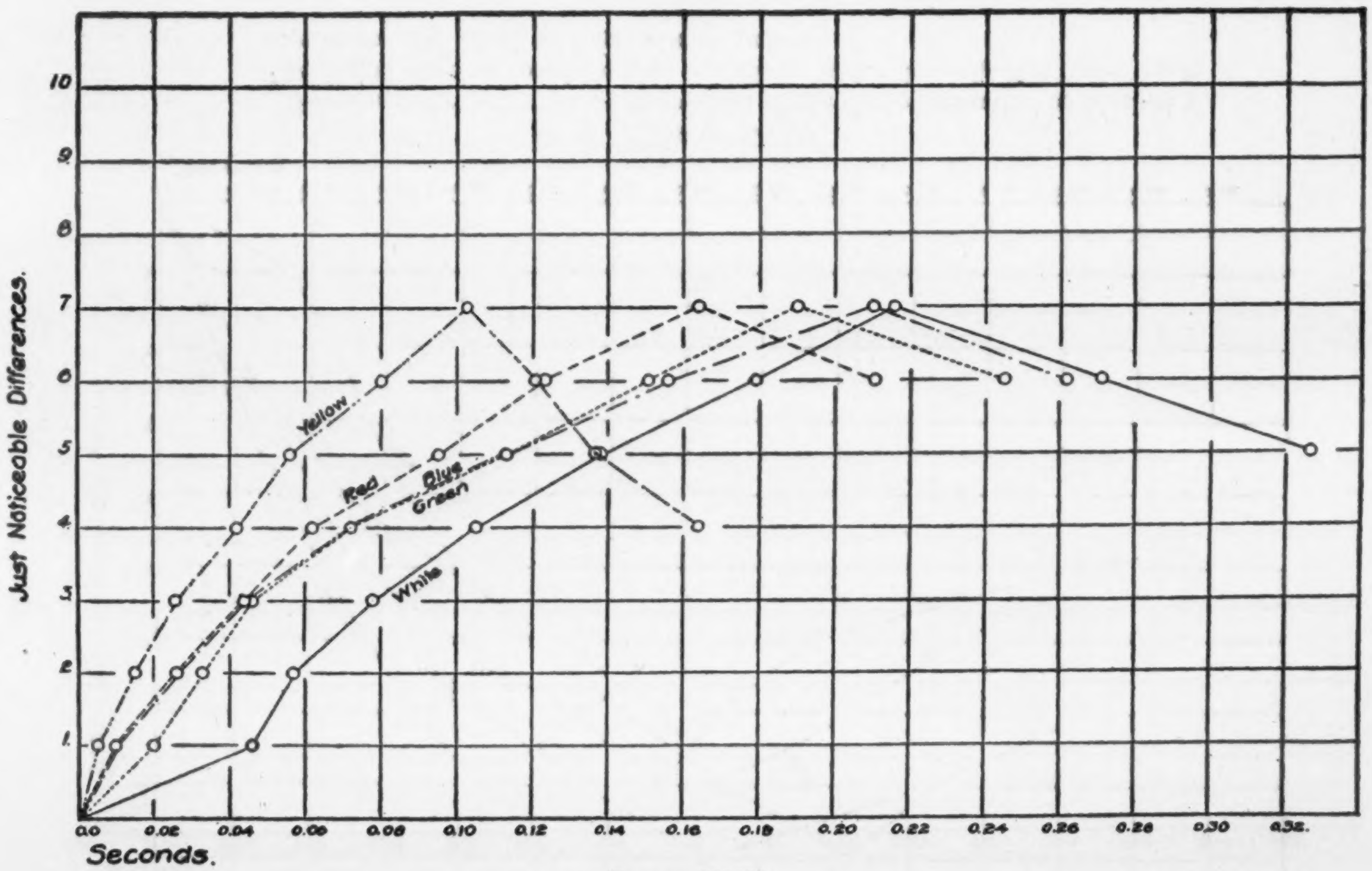

FIGURE XVII

Showing the results of a determination of the rise of sensation by Method 3. The lights used to produce the sensations under investigation were made photometrically equal at 0.057 meter-candles.

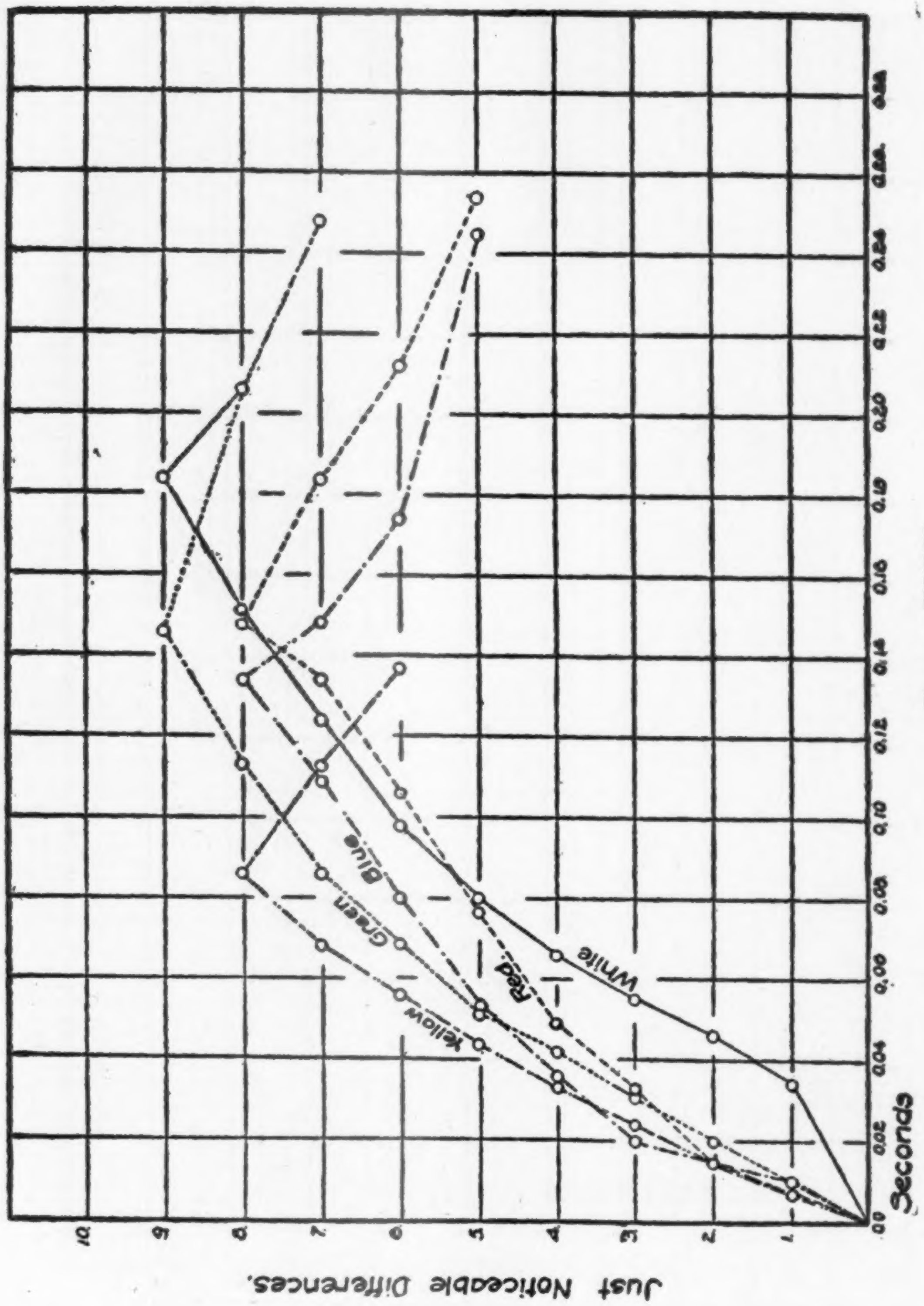

FIGURE XVIII

Showing the results of a determination of the rise of sensation by Method 3. The lights used to produce the sensations under investigation were made photometrically equal at 0.151 meter-candles.

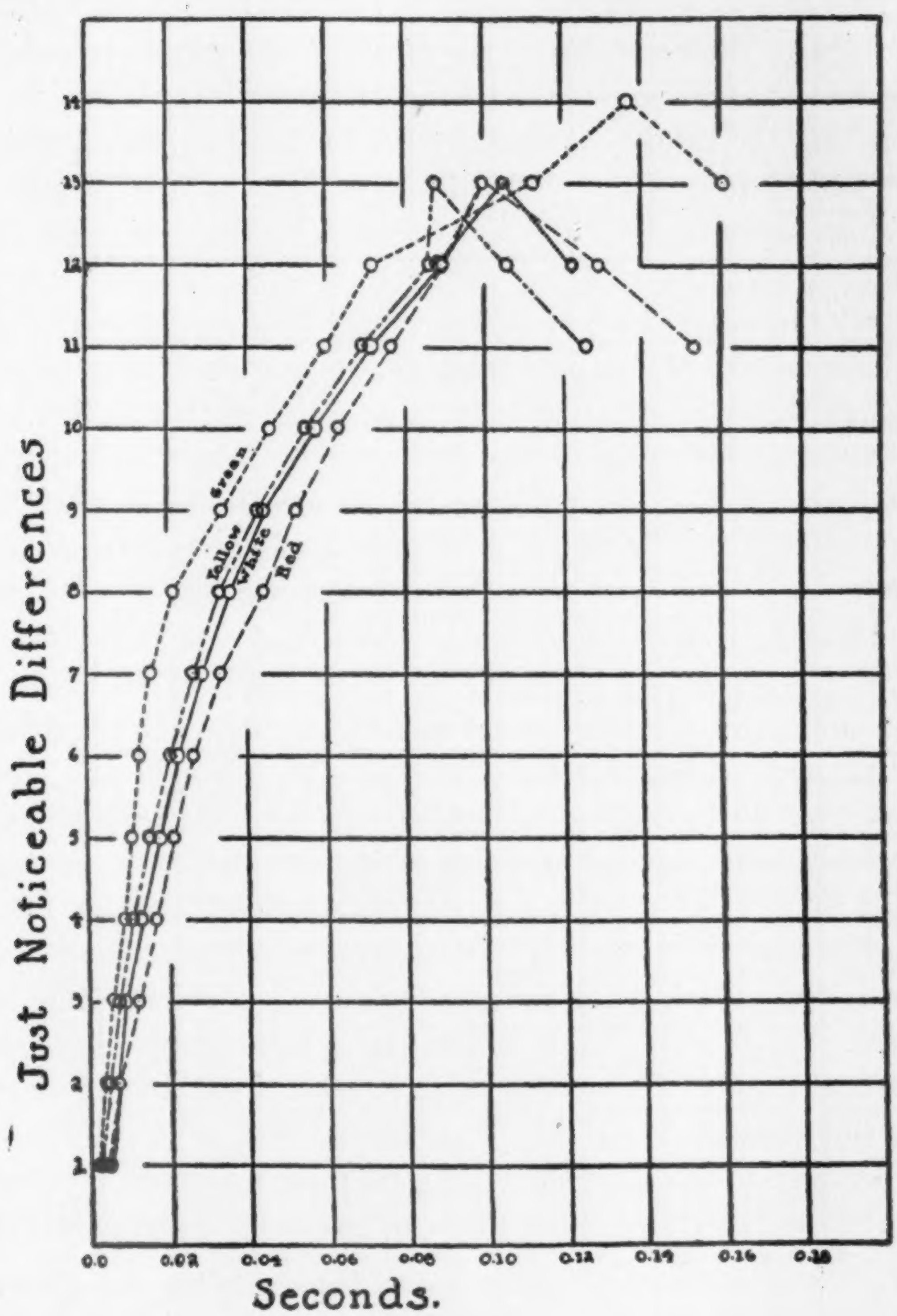

FIGURE XIX

Showing the results of a determination of the rise of sensation by Method 3. The lights to produce the sensations under investigation were made photometrically equal at 1.21 meter-candles.

optimum exposures at appropriate points in the charts. These charts are shown in Figures XX and XXI. An inspection of the charts shows a close agreement in the curves representing the rise of sensation for the three new methods. It will be seen also that the results obtained by the methods of Broca and Sulzer and Exner, in the form in which we have used them, show a close agreement with those obtained by the new methods, in the only way in which they can be compared. That is, they give nearly the same value for the optimum time of exposure. Kunkel's method, it will be noted, shows a poorer agreement, although the point of disagreement, as stated earlier in this paper, falls within the change in the exposure that would be required to produce a just noticeable difference in sensation. A much more serious objection to its use than its lack of agreement with other methods, is its infeasibility and cumbersomeness of application. Compared in this latter regard, which is a very important one, from the laboratory point of view, it is the least feasible of all the methods. Of the four remaining methods, the method of Broca and Sulzer is more convenient and feasible in practice than that of Exner; and Method 3 is the most and Method 2 the least convenient and feasible of the new methods. From the point of view of *a priori* sureness of principle Methods 1 and 3 have, in our opinion, the greatest claim to consideration; and of these Method 3 has a great advantage in convenience and feasibility of application. For general laboratory purposes, it is the most promising of any that we have taken into account in making this study.[43]

We have in the foregoing study attempted to make a comparison of the results of the methods of previous investigators with

[43] So far as convenience of use is concerned, it is only fair to say, however, that in any given case, the equipment of the laboratory must, of course, be taken into consideration. If there is any difference in the ease or accuracy with which the variations in time and the variations in intensity can be made with the apparatus available, this might, perhaps, determine the choice between the two methds. But even from the view-point of simplicity of the equipment needed, Method 3 has a decided advantage over Method 1 and 2. However, if the determination of the rise of sensation is to be made for a great number of intensities of light, Method 1 has a greater claim to consideration from the standpoint of relative quickness and speed of operation than is indicated above.

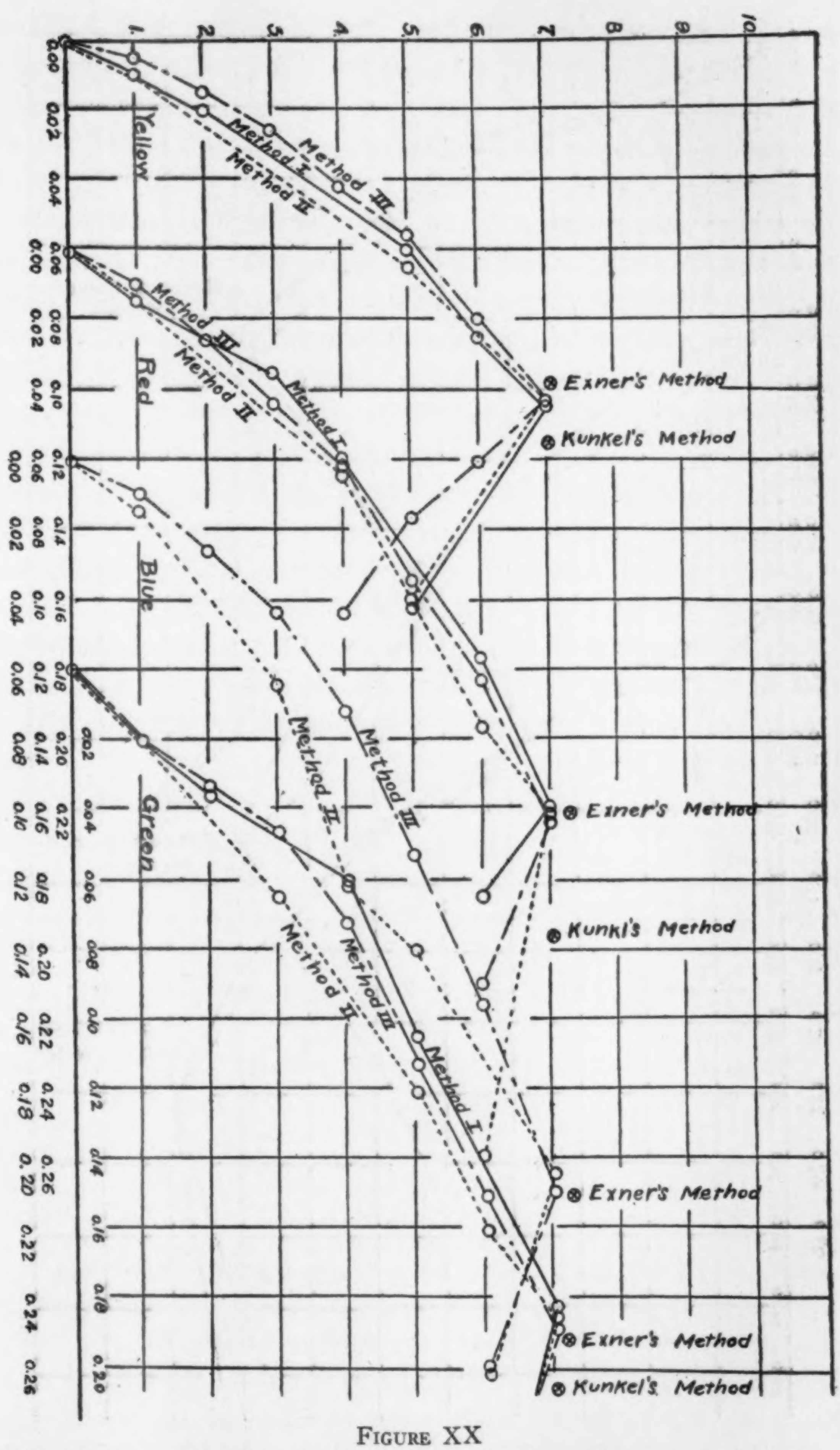

FIGURE XX

Showing a comparison of the results of a determination of the rise of sensation by the different methods used in this investigation. The lights used to produce the sensations under investigation were made photometrically equal at 0.057 meter-candles.

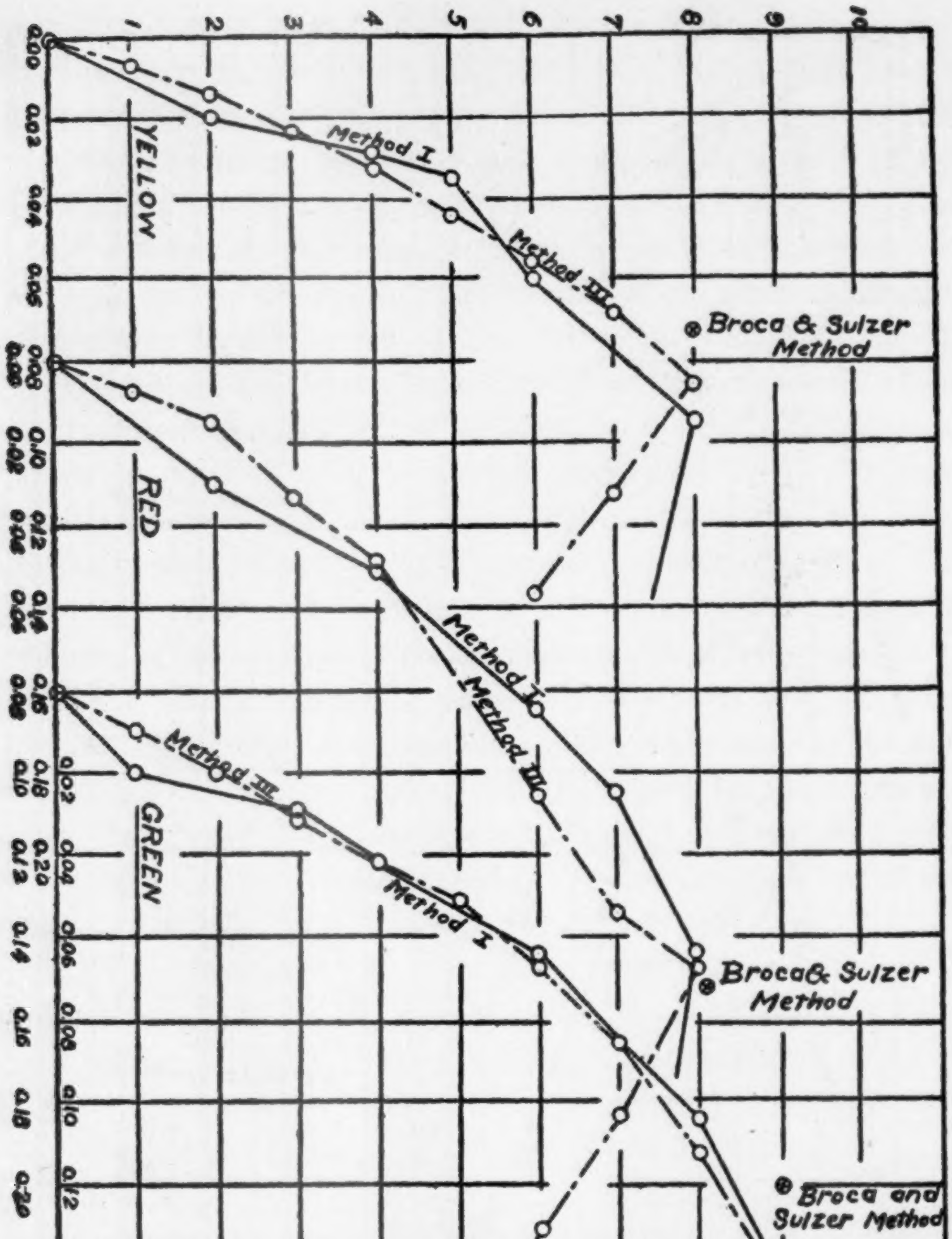

FIGURE XXI

Showing a comparison of the results of a determination of the rise of sensation by the different methods used in this investigation. The lights used to produce the sensations under investigation were made photometrically equal at 0.151 meter-candles.

the same observer and with a similar technique and apparatus. It would be a matter of a great deal of interest if we could also compare the results obtained by the originators of these methods with our own; but, as we have already stated in giving our reason for making the comparative study ourselves, this has not been possible. In reviewing all of the results which have been obtained by these investigators there seem to be but two sets which can be compared with our own. These are the results given by Büchner and by Lough on the time that is required by differen intensities of white light to arouse the maximum of sensation. In all other cases the specifications of the light with regard to composition and intensity were too fragmentary and indefinite to allow of any comparison; or, in the case of Broca and Sulzer an entirely different range of intensities was used. It is rather remarkable that in comparing these results with ours so close an agreement should be found considering that the lights were only of the same order of intensity and that we have no *a priori* reason to suppose that the lag is the same for all observers. Table XVII shows a comparison of these sets of results.

TABLE XVII

Observer	*Intensity in meter-candles*	*Time necessary to arouse maximum response*
Bills	0.057	0.216
Büchner	0.072	0.230
Lough	0.097	0.148
Büchner	0.145	0.200
Bills	0.150	0.180
Büchner	0.260	0.120
Lough	0.288	0.110
Bills	1.211	0.105
Lough	1.552	0.100
Lough	6.208	0.080
Lough	24.832	0.090

It is very probable that there is a closer agreement from observer to observer in the amount of lag for white than for colored light. The author hopes as one of the features of a later work to make a comparative study of this phenomenon for both colored and white light with a number of observers using the same method of making the determination and the same intensity of light.

CONCLUSION

In conclusion, the following points may be mentioned: (1) Previous investigators of the lag in the responses of the retina to lights of different compositions and intensities have worked with one method alone and have not, as a rule, specified their conditions of experimentation with sufficient definiteness and precision that their work can be reproduced or their results be compared with each other. Moreover, only one of the methods used by them was designed to give the rate of rise of sensation to its maximum as well as the time required for the maximum to be reached; and the principles on which this method is based are open to criticism.

(2) The object of the present study has been to devise new methods and to compare the results obtained by them with those obtained by the more promising of the older methods with the same observer, under the same conditions of experimentation and with the same wave-lengths and intensities of light. In a preliminary study four of the older methods, with some needed modifications, were chosen for the purposes of this comparison.

(3) A very close agreement in the rate of rise of sensation was obtained by the new methods for each kind and intensity of light used. A close agreement also was obtained by all of the new methods, and two of the old for the time required for sensation to reach its maximum in each of the cases compared. A poorer agreement was obtained by the method of Kunkel and a still poorer one by the method of Dürr. Both of these latter methods also proved very difficult and cumbersome of application.

(4) Of the new methods, 1 and 3 seem to have the greatest *a priori* sureness of principle, also to agree the most closely with each other in result. Of these, 3 is the most feasible and convenient of application and of all the methods we have used, seems to be the most promising for general laboratory purposes.

(5) A different rate of rise of sensation is found for the dif-

ferent wave-lengths and for white light. That is, the retina is not only selective in the amount of its response to wave-length, but it is selective also in the lag it shows in giving its full response. This selectiveness in lag of response also varies with the intensity of the light used.

(6) With the highest intensity of light used, 1.211 meter candles, the order of rate of rise (Method 3) from fastest to slowest, up to within two just noticeable differences of the maximum for green, was green, yellow, white, and red. At this point green lags behind the other colors. Blue was not used in this determination because it could not be obtained of the required photometric value with our apparatus. With the lowest intensity of light used, 0.057 meter candles, the order was yellow, red, blue, green and white. With the intermediate intensity 0.151 meter candles the order varies at different stages in the rise. Near the maximum it is yellow, green, blue, white, and red. Near the threshold it is red, yellow, blue, green, and white. Farther up, near the middle of the course (at the third just noticeable difference), it is blue, yellow, green, red, and white.

(7) With increase of intensity of light there was a decrease in the time required to produce the maximum response. This decrease was more rapid for green and blue and slower for red and yellow.

(8) It was stated in our introductory section that one of the objects of this comparative study of methods was to find one that would be sufficiently feasible in operation to be used in an investigation of the characteristic difference in the results obtained by different observers with the equality of brightness and flicker photometers. Method 3 is recommended for this purpose. In this investigation determinations of lag and photometric determinations should be made by the same observers for the same kinds and intensities of light with the object of finding out whether the deviations of the photometric balance obtained by the method of flicker from that obtained by the equality of brightness method are, for a given observer, in accord with what might be expected from the amount and distribution of lag for that observer. An investigation of this kind is already in progress in the Bryn Mawr laboratory.